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Hall et al.

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(54) **DIFFERENTIAL MICROPHONE WITH SEALED BACKSIDE CAVITIES AND DIAPHRAGMS COUPLED TO A ROCKING STRUCTURE THEREBY PROVIDING RESISTANCE TO DEFLECTION UNDER ATMOSPHERIC PRESSURE AND PROVIDING A DIRECTIONAL RESPONSE TO SOUND PRESSURE**

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(73) Assignee: **Board of Regents, The University of Texas System**, Austin, TX (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 218 days.

(21) Appl. No.: **13/441,079**

(22) Filed: **Apr. 6, 2012**

(65) **Prior Publication Data**

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Related U.S. Application Data

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(51) **Int. Cl.**
H04R 25/00 (2006.01)
H04R 23/00 (2006.01)

(52) **U.S. Cl.**
CPC ***H04R 23/00*** (2013.01)
USPC **381/175**; 381/174; 381/178; 381/355; 381/356; 381/361; 381/369; 438/53; 257/678; 257/723; 73/504.01

(58) **Field of Classification Search**
None
See application file for complete search history.

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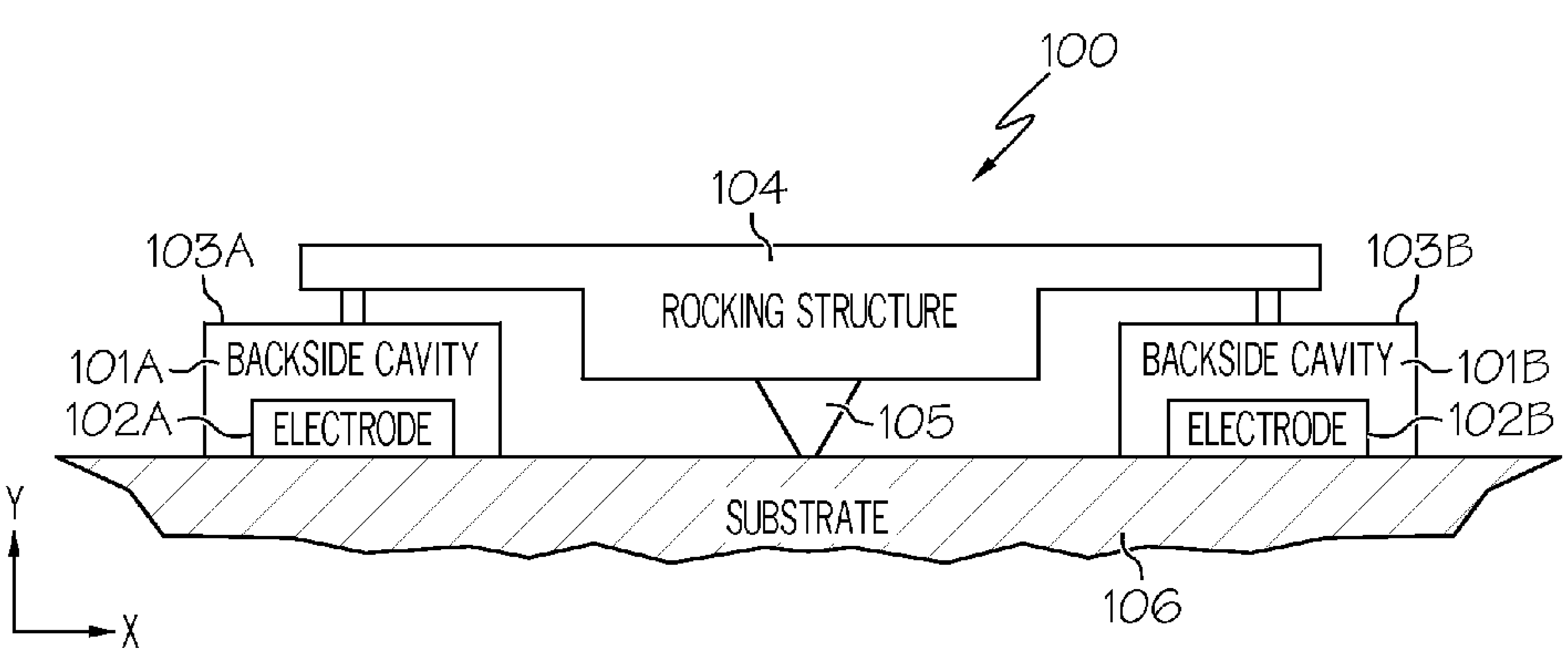
(57) **ABSTRACT**

A vacuum sealed directional microphone and methods for fabricating said vacuum sealed directional microphone. A vacuum sealed directional microphone includes a rocking structure coupled to two vacuum sealed diaphragms which are responsible for collecting incoming sound and deforming under sound pressure. The rocking structure's resistance to bending aids in reducing the deflection of each diaphragm under large atmospheric pressure. Furthermore, the rocking structure exhibits little resistance about its pivot thereby enabling it to freely rotate in response to small pressure gradients characteristic of sound. The backside cavities of such a device can be fabricated without the use of the deep reactive ion etch step thereby allowing such a microphone to be fabricated with a CMOS compatible process.

21 Claims, 13 Drawing Sheets



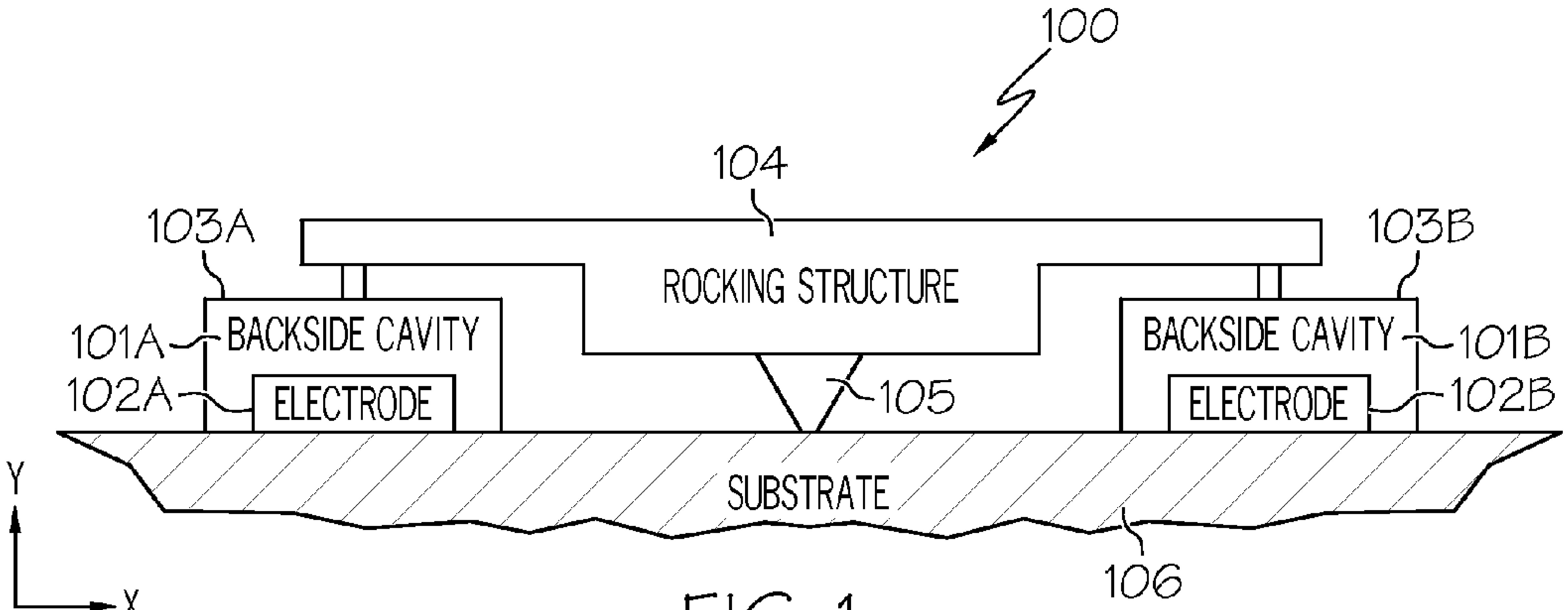


FIG. 1

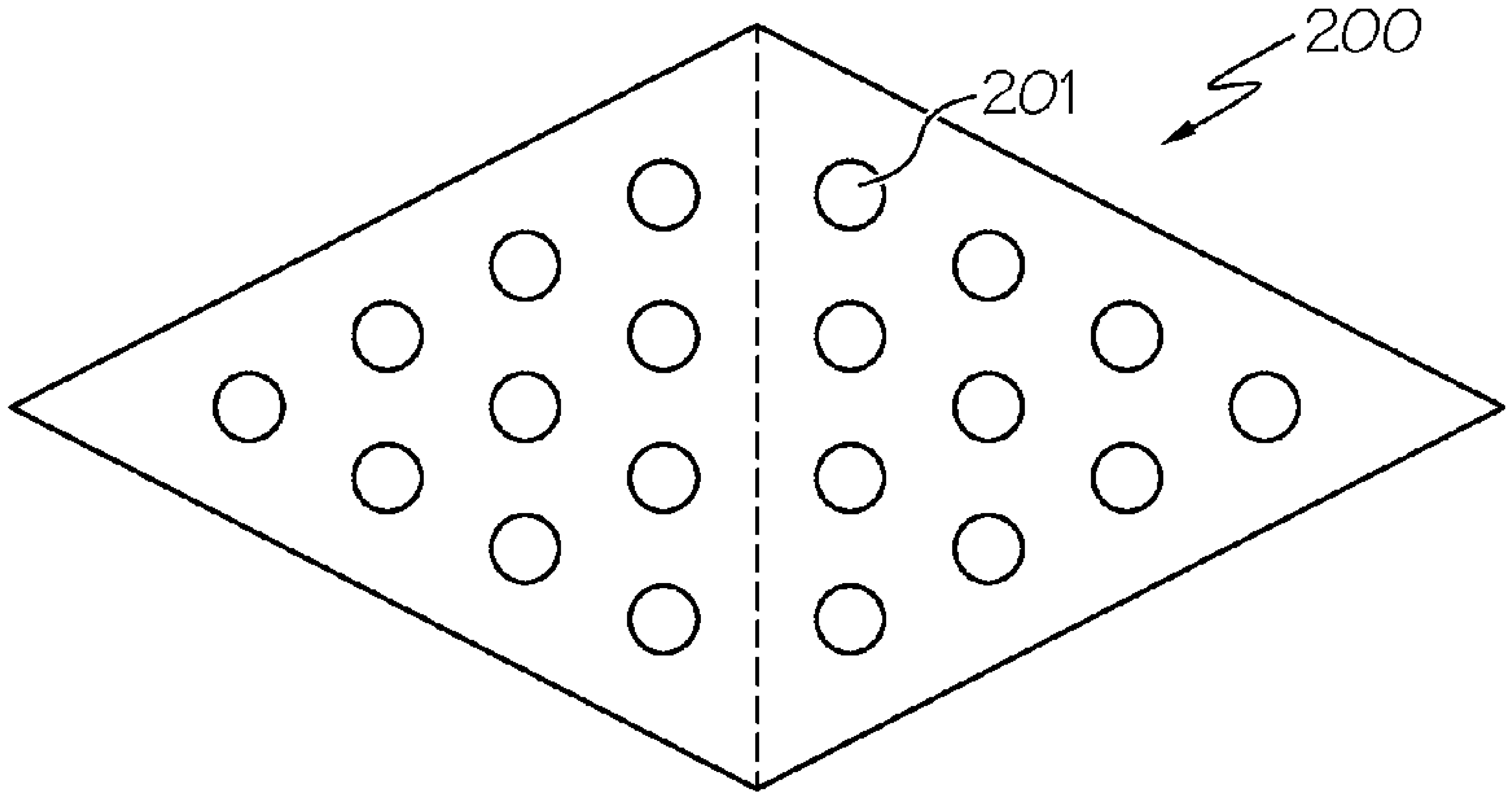


FIG. 2

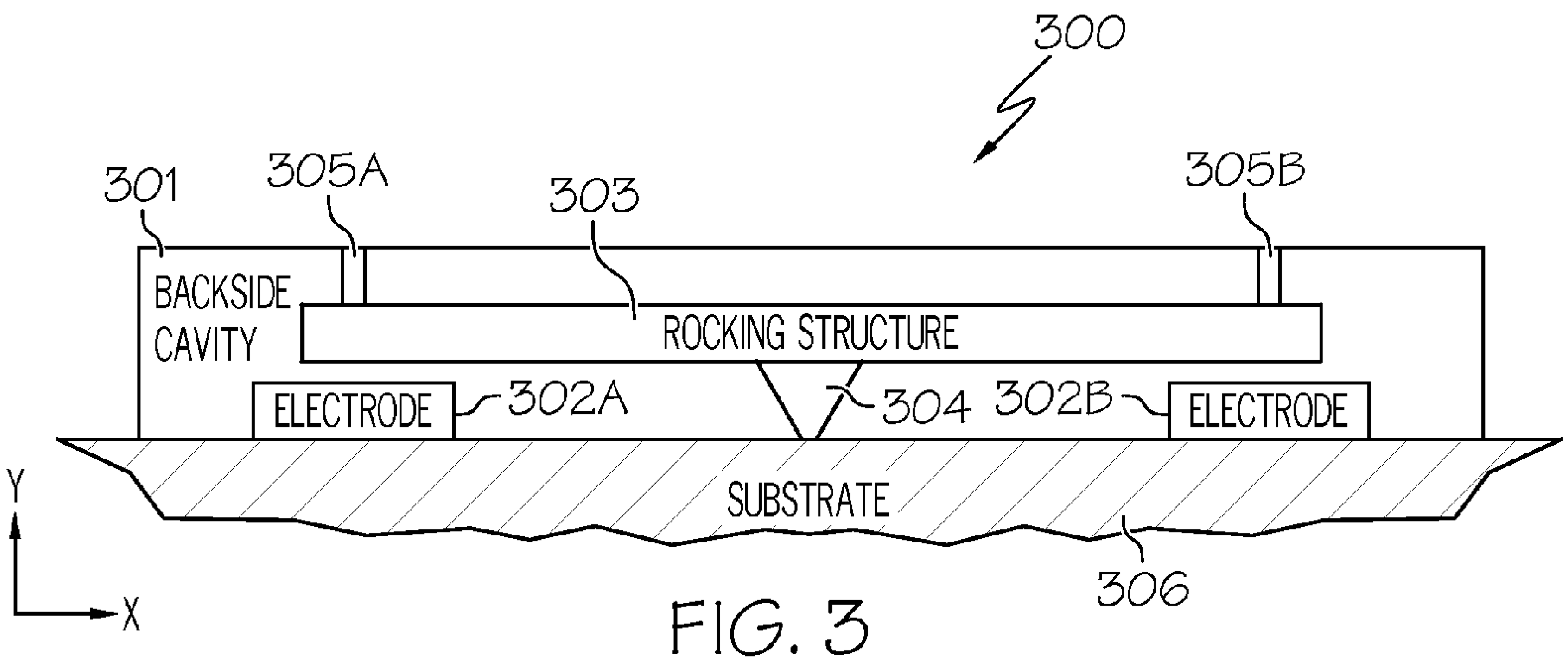
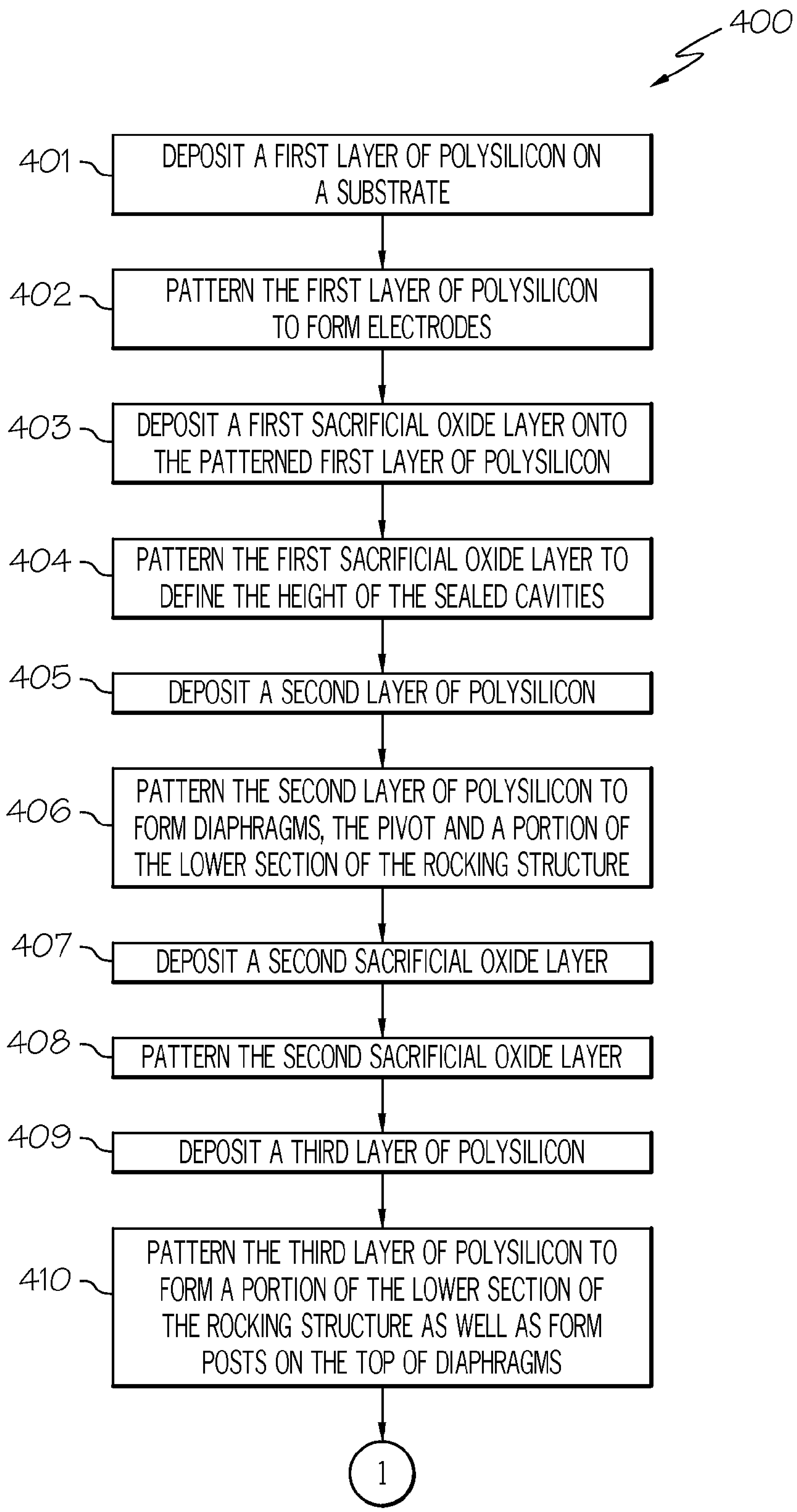


FIG. 3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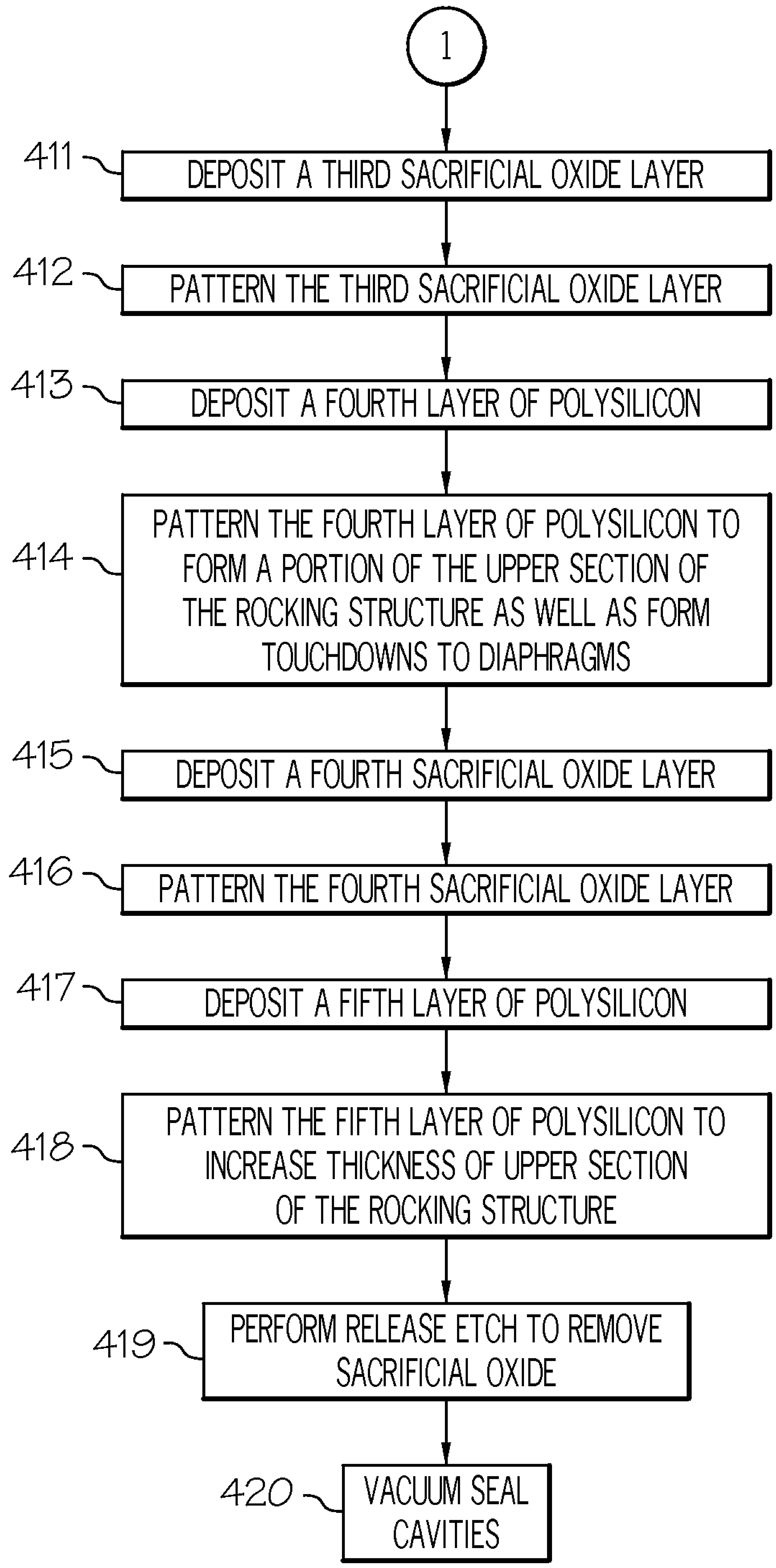
401 DEPOSIT A FIRST LAYER OF POLYSILICON ON A SUBSTRATE
402 PATTERN THE FIRST LAYER OF POLYSILICON TO FORM ELECTRODES
403 DEPOSIT A FIRST SACRIFICIAL OXIDE LAYER ONTO THE PATTERNED FIRST LAYER OF POLYSILICON
404 PATTERN THE FIRST SACRIFICIAL OXIDE LAYER TO DEFINE THE HEIGHT OF THE SEALED CAVITIES
405 DEPOSIT A SECOND LAYER OF POLYSILICON
406 PATTERN THE SECOND LAYER OF POLYSILICON TO FORM DIAPHRAGMS, THE PIVOT AND A PORTION OF THE LOWER SECTION OF THE ROCKING STRUCTURE
407 DEPOSIT A SECOND SACRIFICIAL OXIDE LAYER
408 PATTERN THE SECOND SACRIFICIAL OXIDE LAYER
409 DEPOSIT A THIRD LAYER OF POLYSILICON
410 PATTERN THE THIRD LAYER OF POLYSILICON TO FORM A PORTION OF THE LOWER SECTION OF THE ROCKING STRUCTURE AS WELL AS FORM POSTS ON THE TOP OF DIAPHRAGMS
1

FIG. 4A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PATTERN THE THIRD SACRIFICIAL OXIDE LAYER
413
DEPOSIT A FOURTH LAYER OF POLYSILICON
414
PATTERN THE FOURTH LAYER OF POLYSILICON TO FORM A PORTION OF THE UPPER SECTION OF THE ROCKING STRUCTURE AS WELL AS FORM TOUCHDOWNS TO DIAPHRAGMS
415
DEPOSIT A FOURTH SACRIFICIAL OXIDE LAYER
416
PATTERN THE FOURTH SACRIFICIAL OXIDE LAYER
417
DEPOSIT A FIFTH LAYER OF POLYSILICON
418
PATTERN THE FIFTH LAYER OF POLYSILICON TO INCREASE THICKNESS OF UPPER SECTION OF THE ROCKING STRUCTURE
419
PERFORM RELEASE ETCH TO REMOVE SACRIFICIAL OXIDE
420
VACUUM SEAL CAVITIES

FIG. 4B

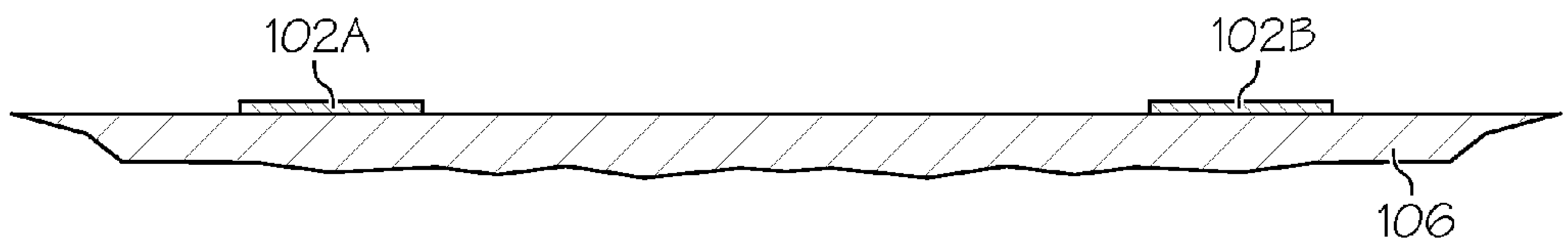


FIG. 5A

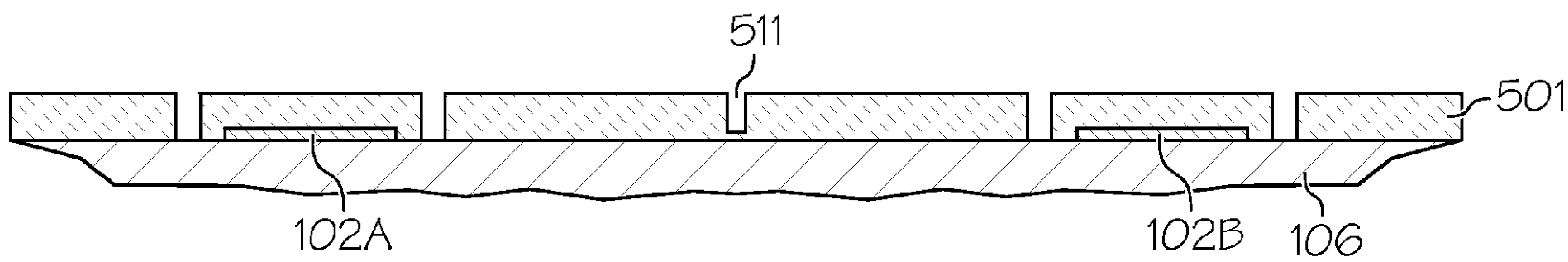


FIG. 5B

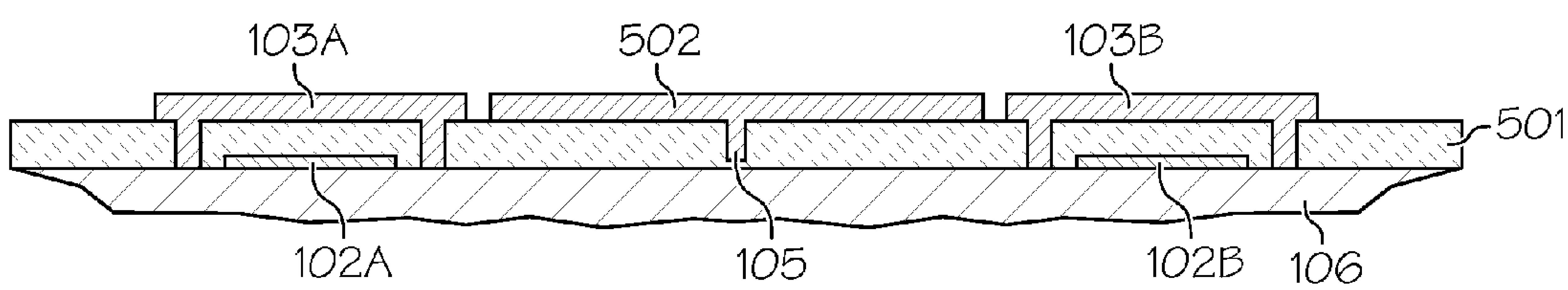


FIG. 5C

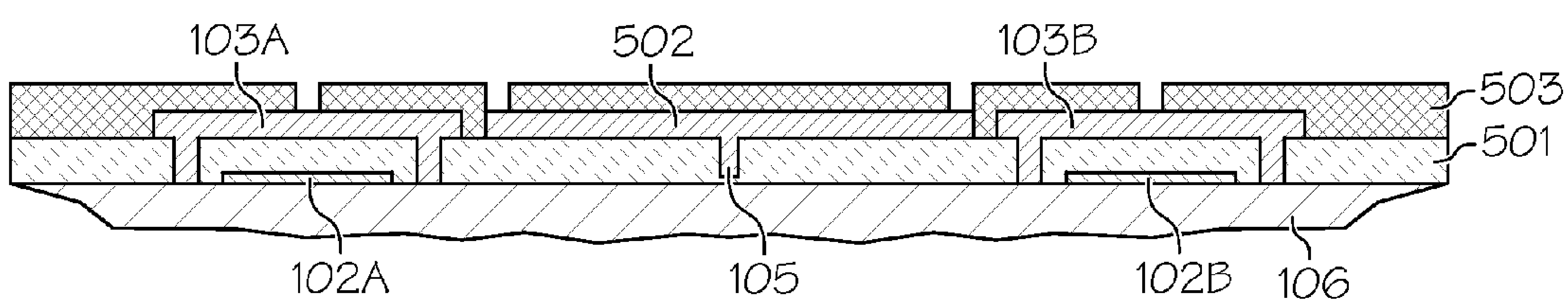


FIG. 5D

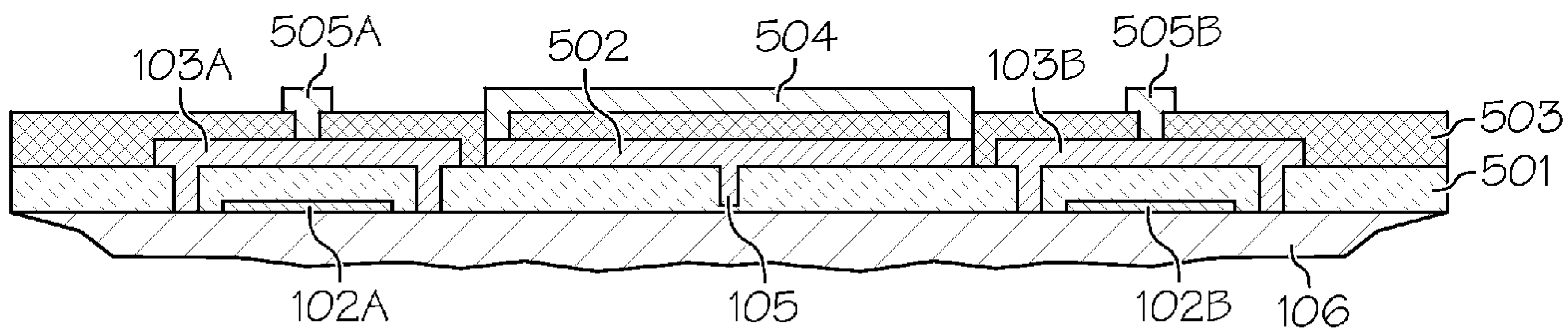


FIG. 5E

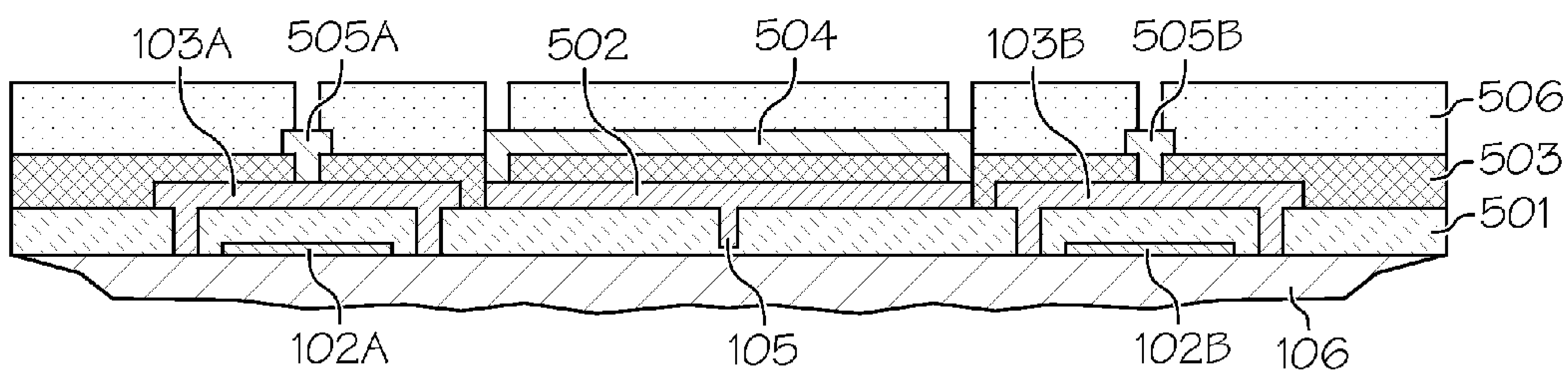


FIG. 5F

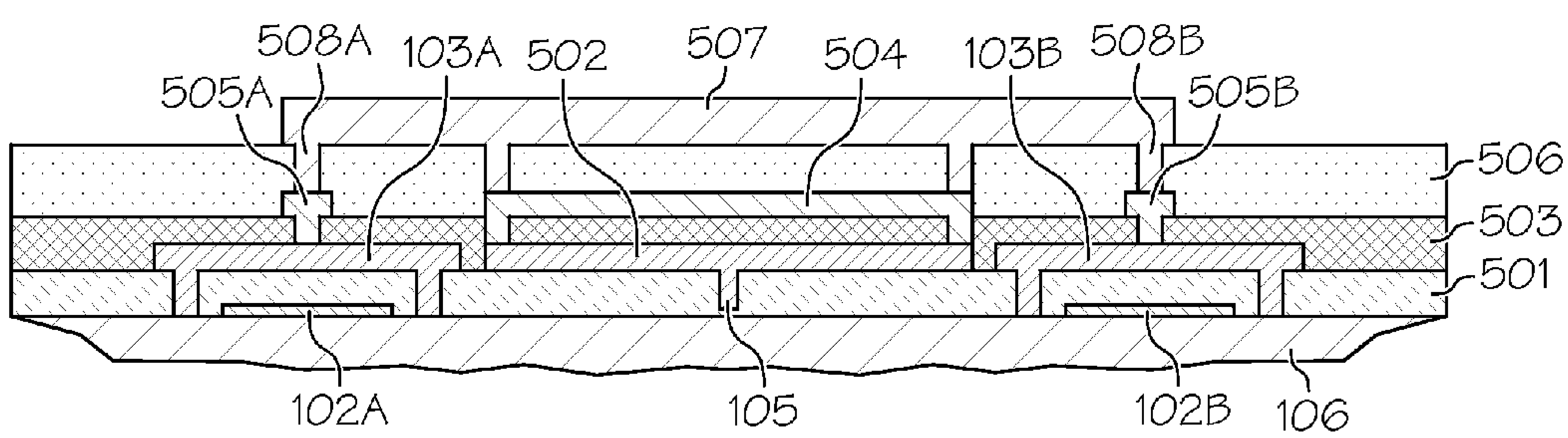


FIG. 5G

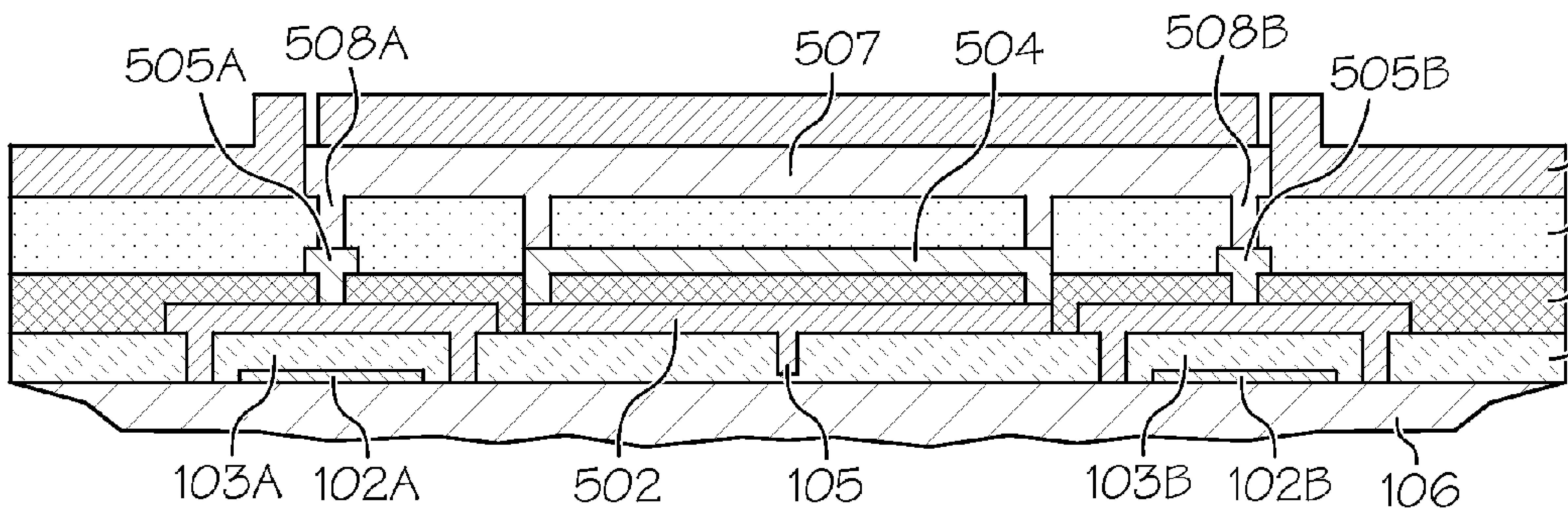


FIG. 5H

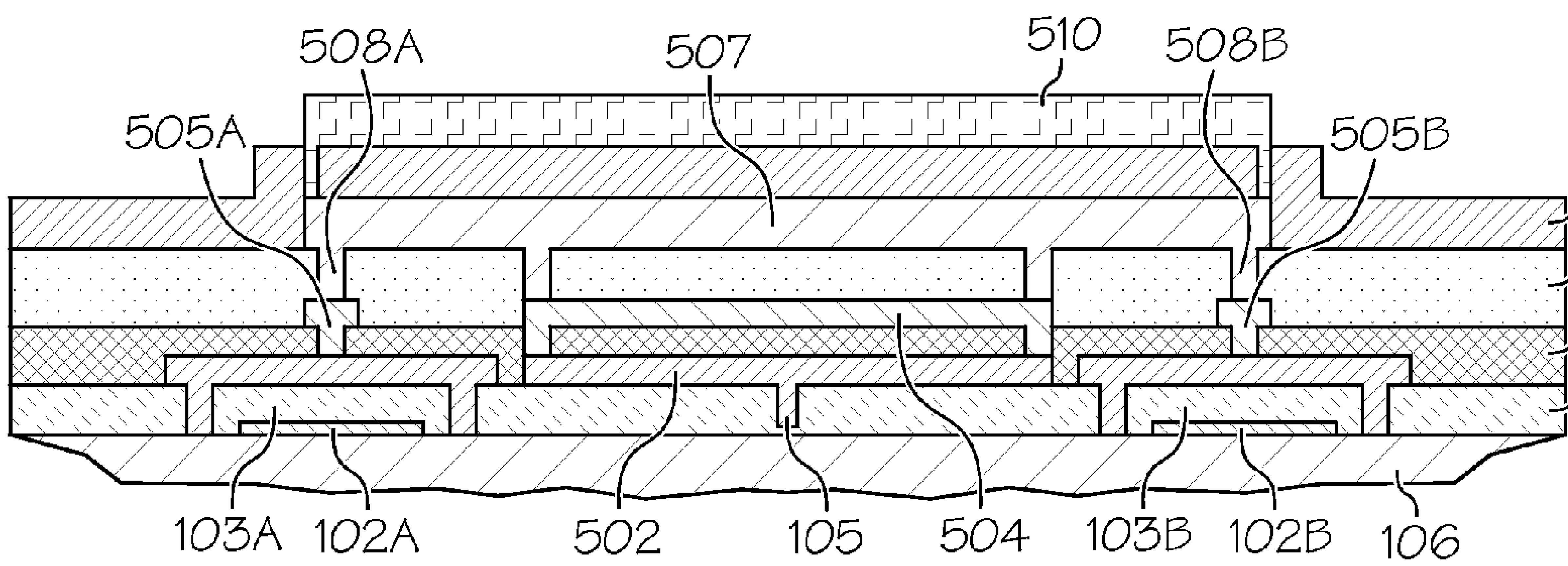


FIG. 5I

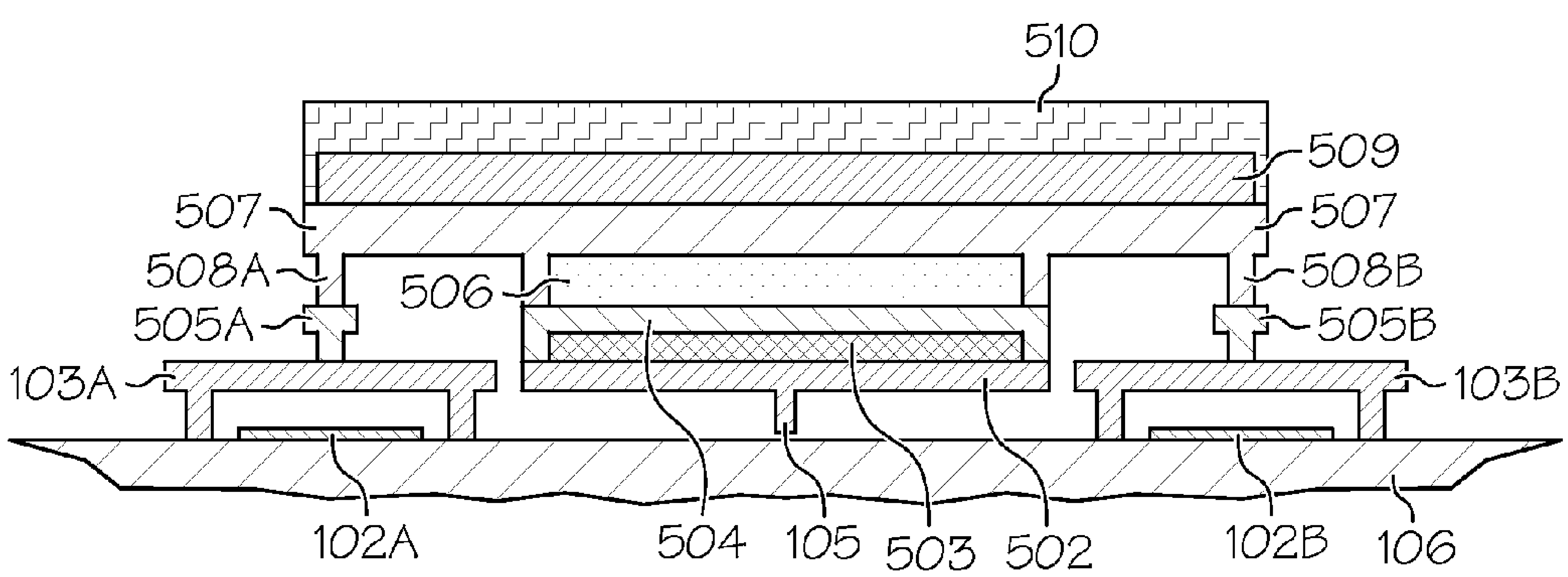
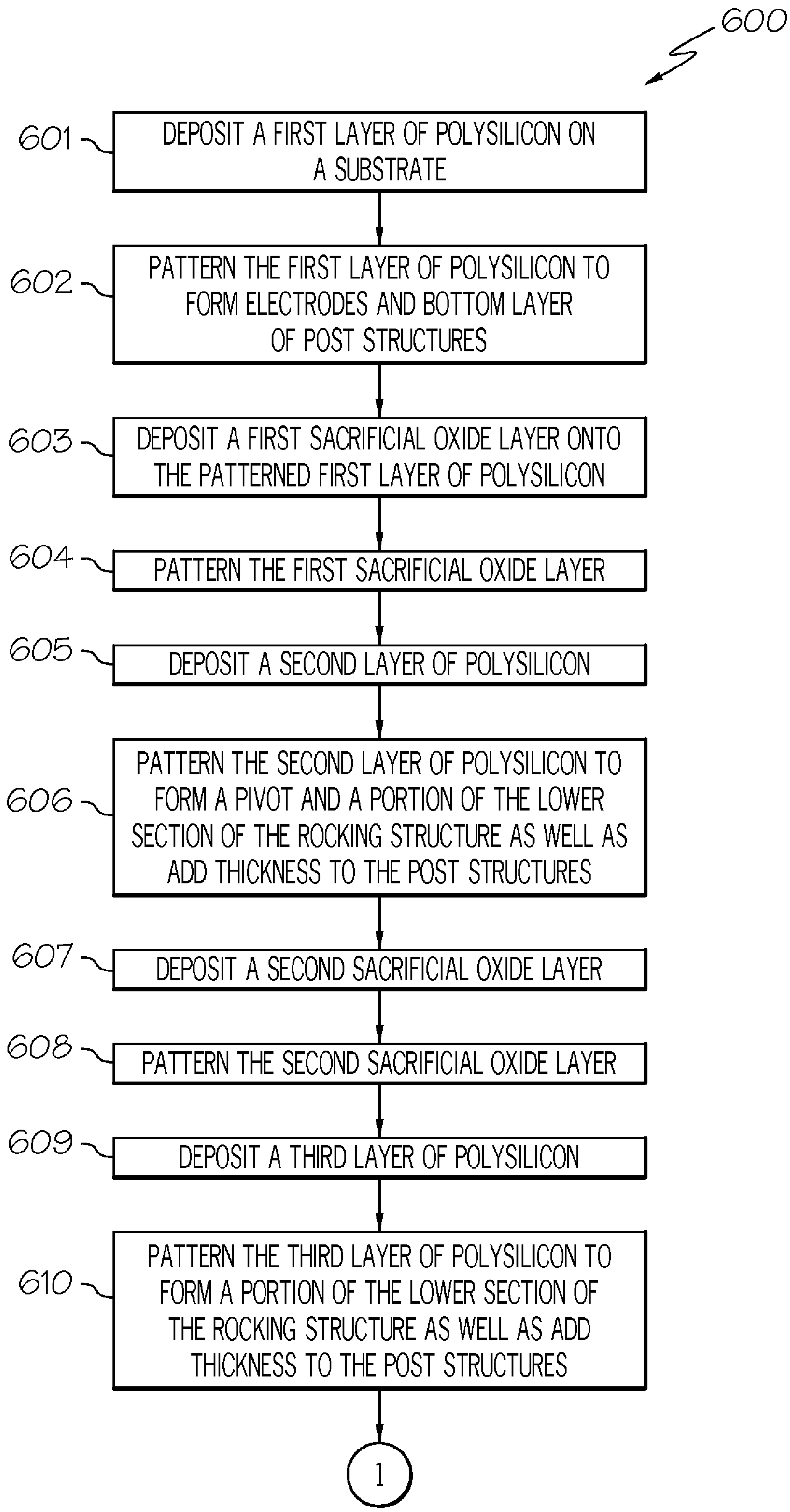


FIG. 5J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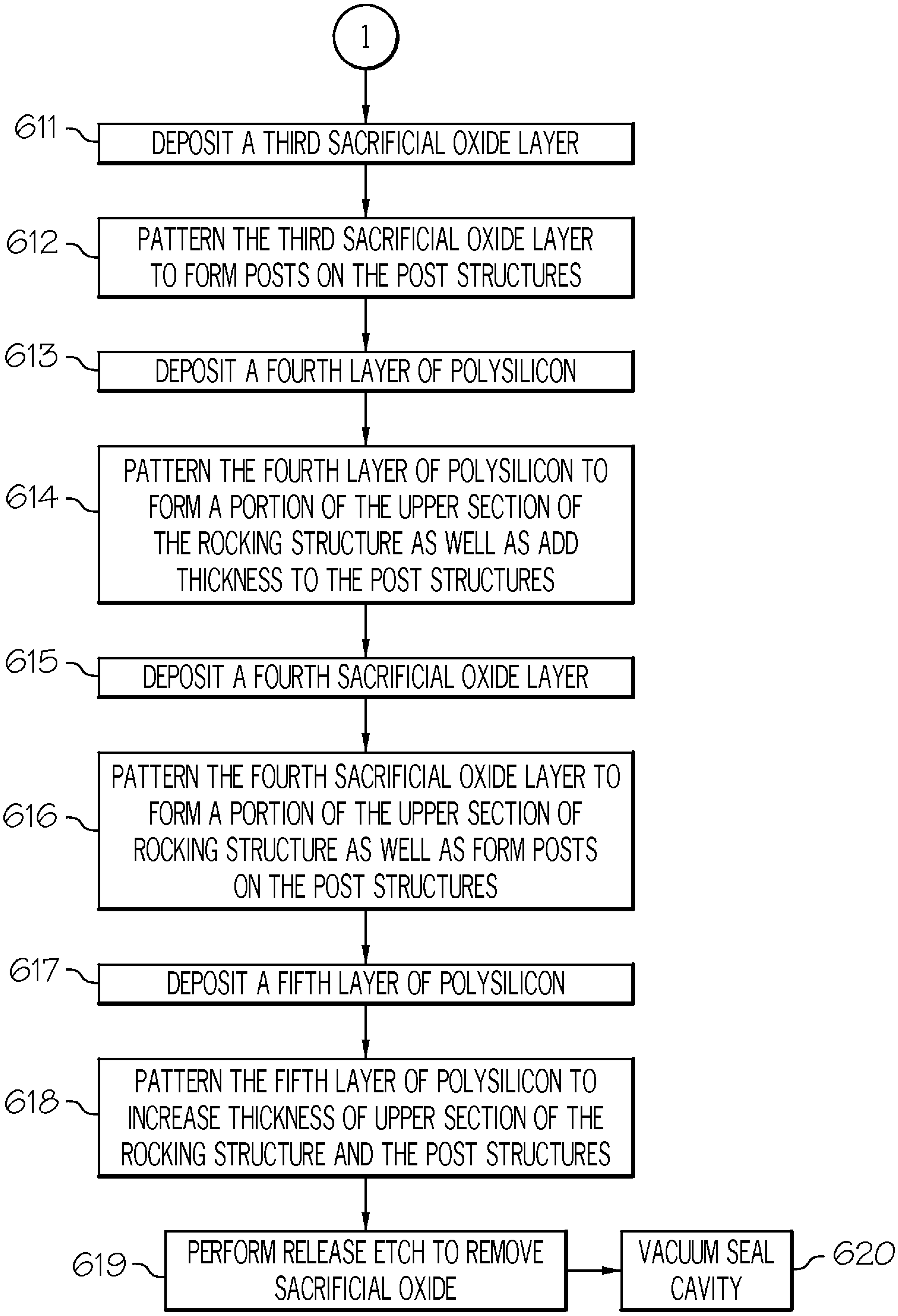
601
DEPOSIT A FIRST LAYER OF POLYSILICON ON A SUBSTRATE
602
PATTERN THE FIRST LAYER OF POLYSILICON TO FORM ELECTRODES AND BOTTOM LAYER OF POST STRUCTURES
603
DEPOSIT A FIRST SACRIFICIAL OXIDE LAYER ONTO THE PATTERNED FIRST LAYER OF POLYSILICON
604
PATTERN THE FIRST SACRIFICIAL OXIDE LAYER
605
DEPOSIT A SECOND LAYER OF POLYSILICON
606
PATTERN THE SECOND LAYER OF POLYSILICON TO FORM A PIVOT AND A PORTION OF THE LOWER SECTION OF THE ROCKING STRUCTURE AS WELL AS ADD THICKNESS TO THE POST STRUCTURES
607
DEPOSIT A SECOND SACRIFICIAL OXIDE LAYER
608
PATTERN THE SECOND SACRIFICIAL OXIDE LAYER
609
DEPOSIT A THIRD LAYER OF POLYSILICON
610
PATTERN THE THIRD LAYER OF POLYSILICON TO FORM A PORTION OF THE LOWER SECTION OF THE ROCKING STRUCTURE AS WELL AS ADD THICKNESS TO THE POST STRUCTURES
1

FIG. 6A


1
611
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612
PATTERN THE THIRD SACRIFICIAL OXIDE LAYER TO FORM POSTS ON THE POST STRUCTURES
613
DEPOSIT A FOURTH LAYER OF POLYSILICON
614
PATTERN THE FOURTH LAYER OF POLYSILICON TO FORM A PORTION OF THE UPPER SECTION OF THE ROCKING STRUCTURE AS WELL AS ADD THICKNESS TO THE POST STRUCTURES
615
DEPOSIT A FOURTH SACRIFICIAL OXIDE LAYER
616
PATTERN THE FOURTH SACRIFICIAL OXIDE LAYER TO FORM A PORTION OF THE UPPER SECTION OF ROCKING STRUCTURE AS WELL AS FORM POSTS ON THE POST STRUCTURES
617
DEPOSIT A FIFTH LAYER OF POLYSILICON
618
PATTERN THE FIFTH LAYER OF POLYSILICON TO INCREASE THICKNESS OF UPPER SECTION OF THE ROCKING STRUCTURE AND THE POST STRUCTURES
619
PERFORM RELEASE ETCH TO REMOVE SACRIFICIAL OXIDE
VACUUM SEAL CAVITY
620

FIG. 6B

FIG. 7A

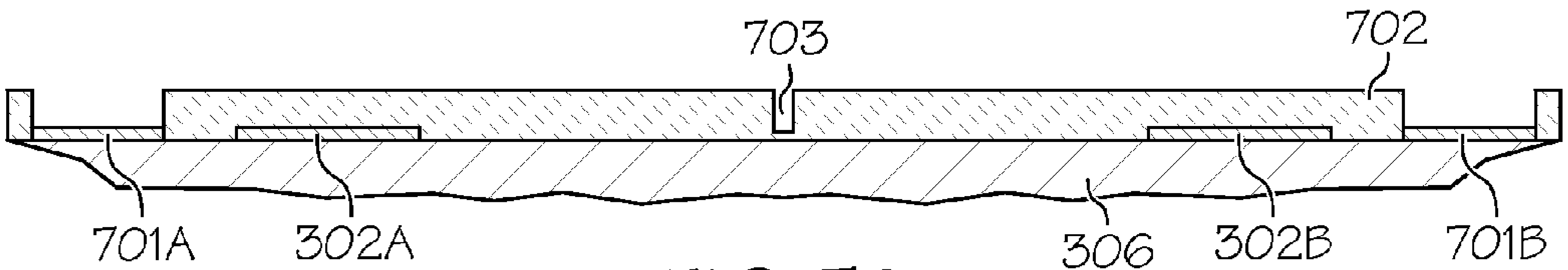

FIG. 7B

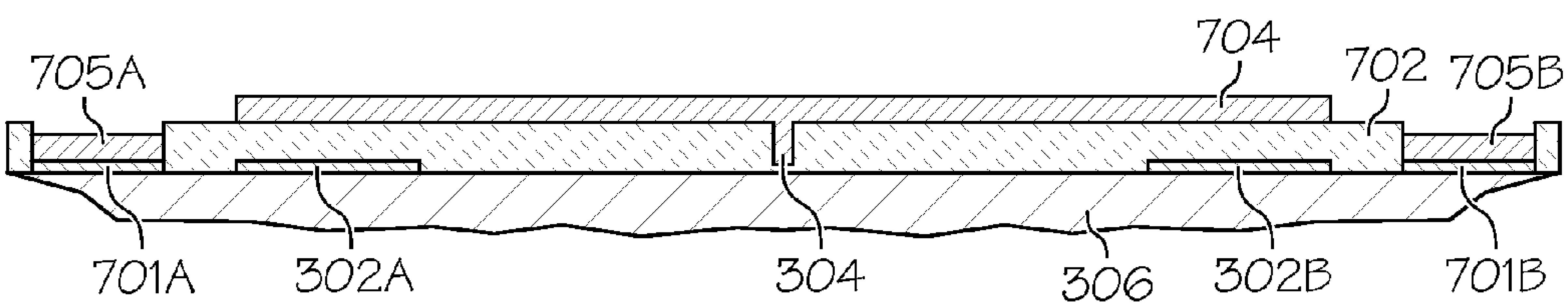

FIG. 7C

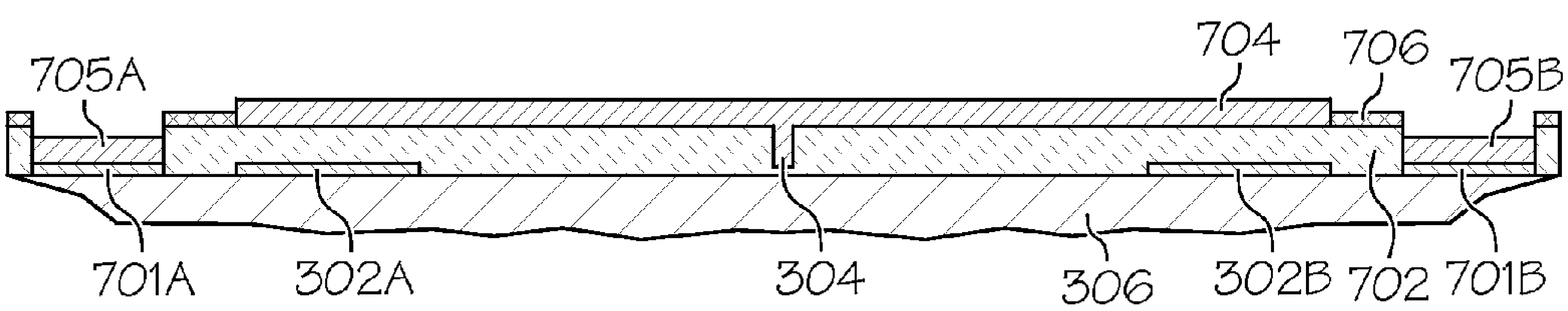

FIG. 7D

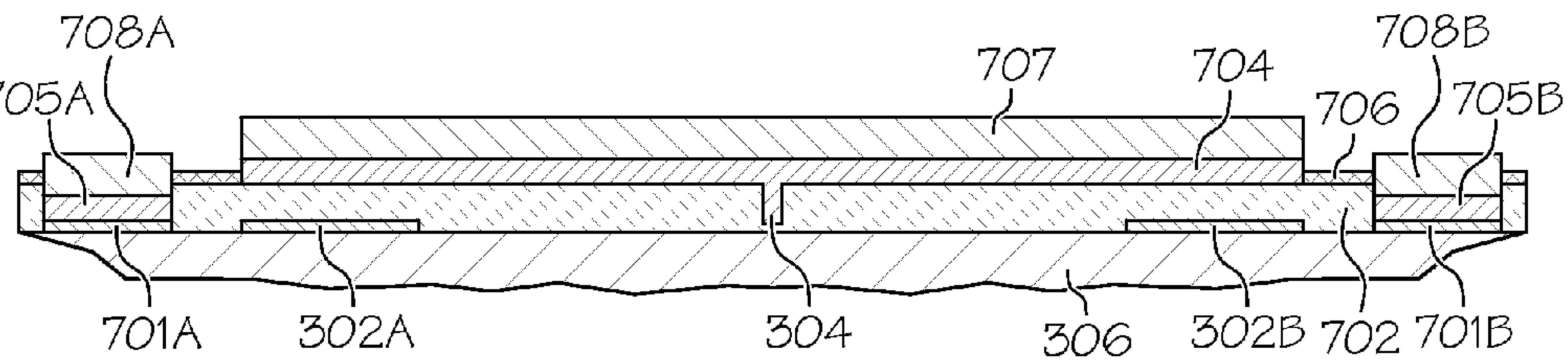

FIG. 7E

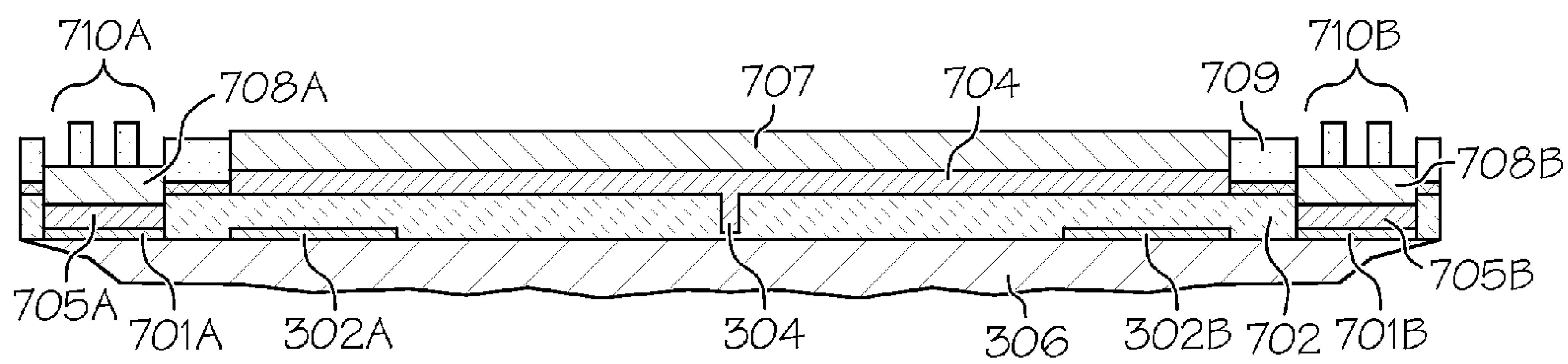

FIG. 7F

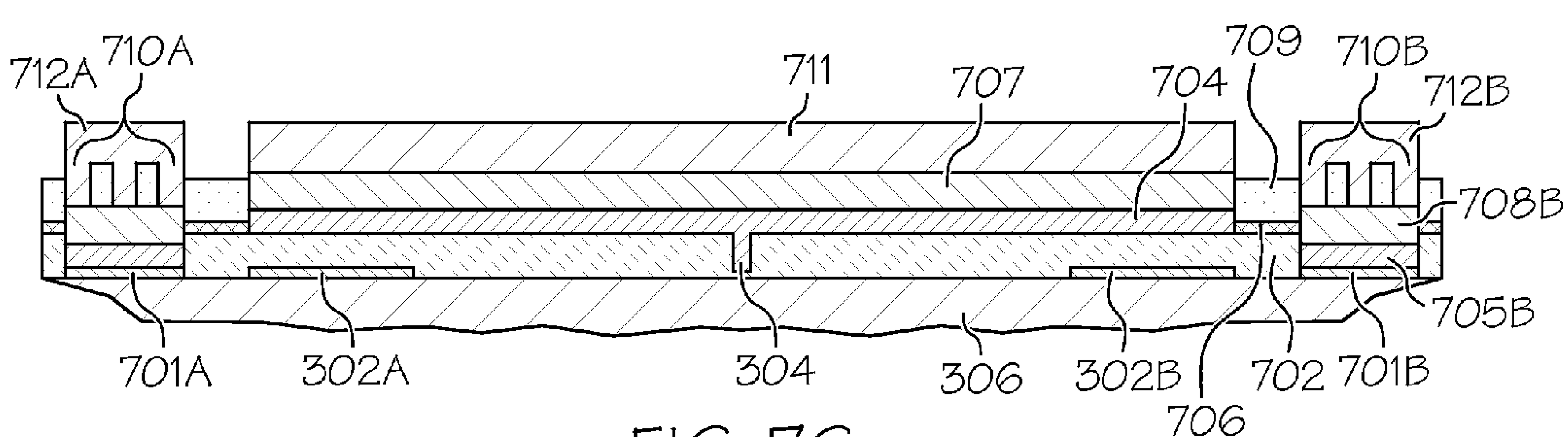

FIG. 7G

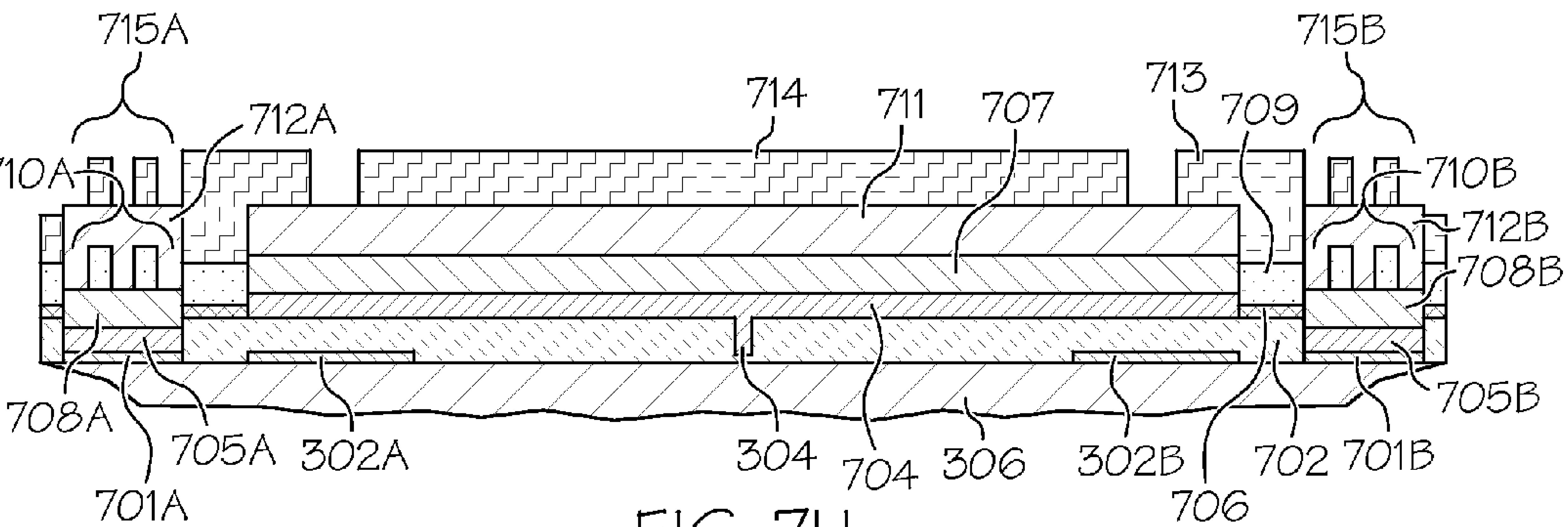

FIG. 7H

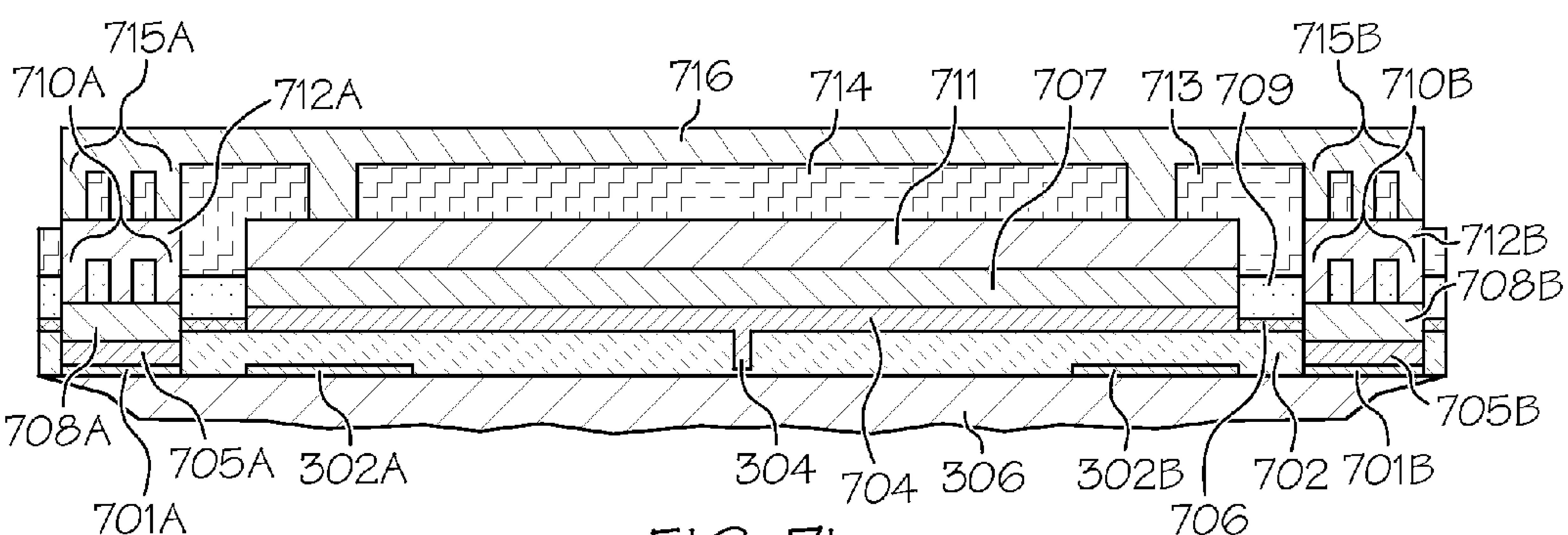

FIG. 7I

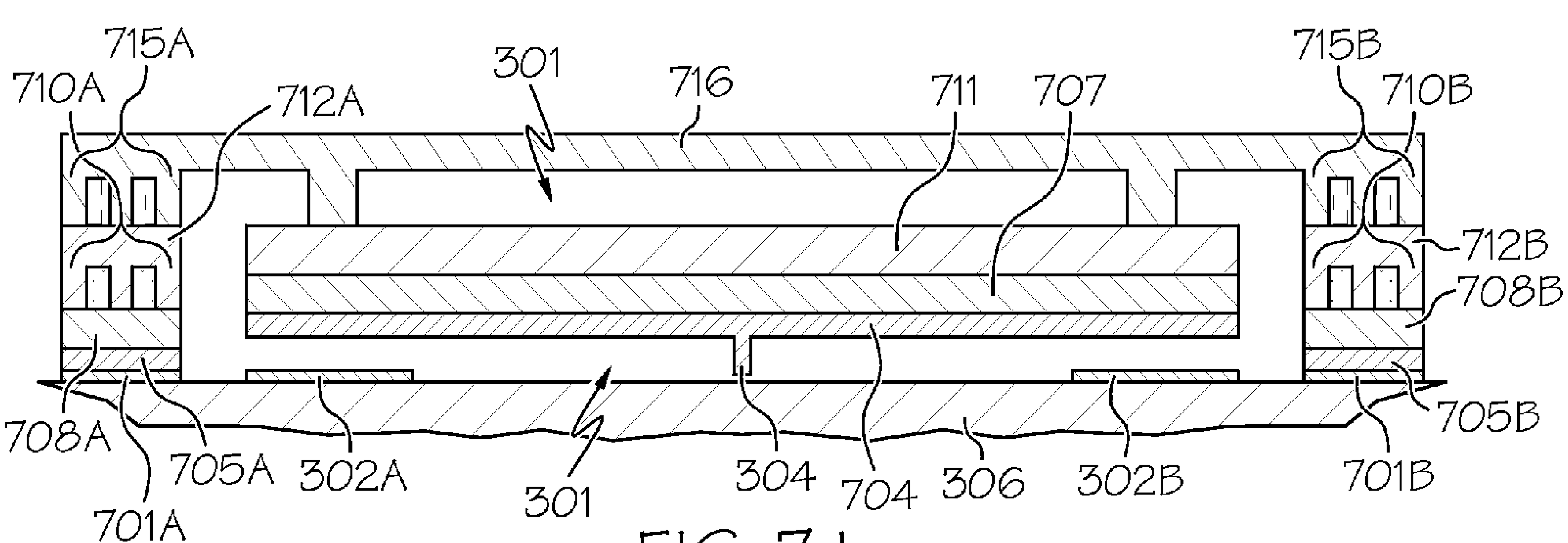

FIG. 7J

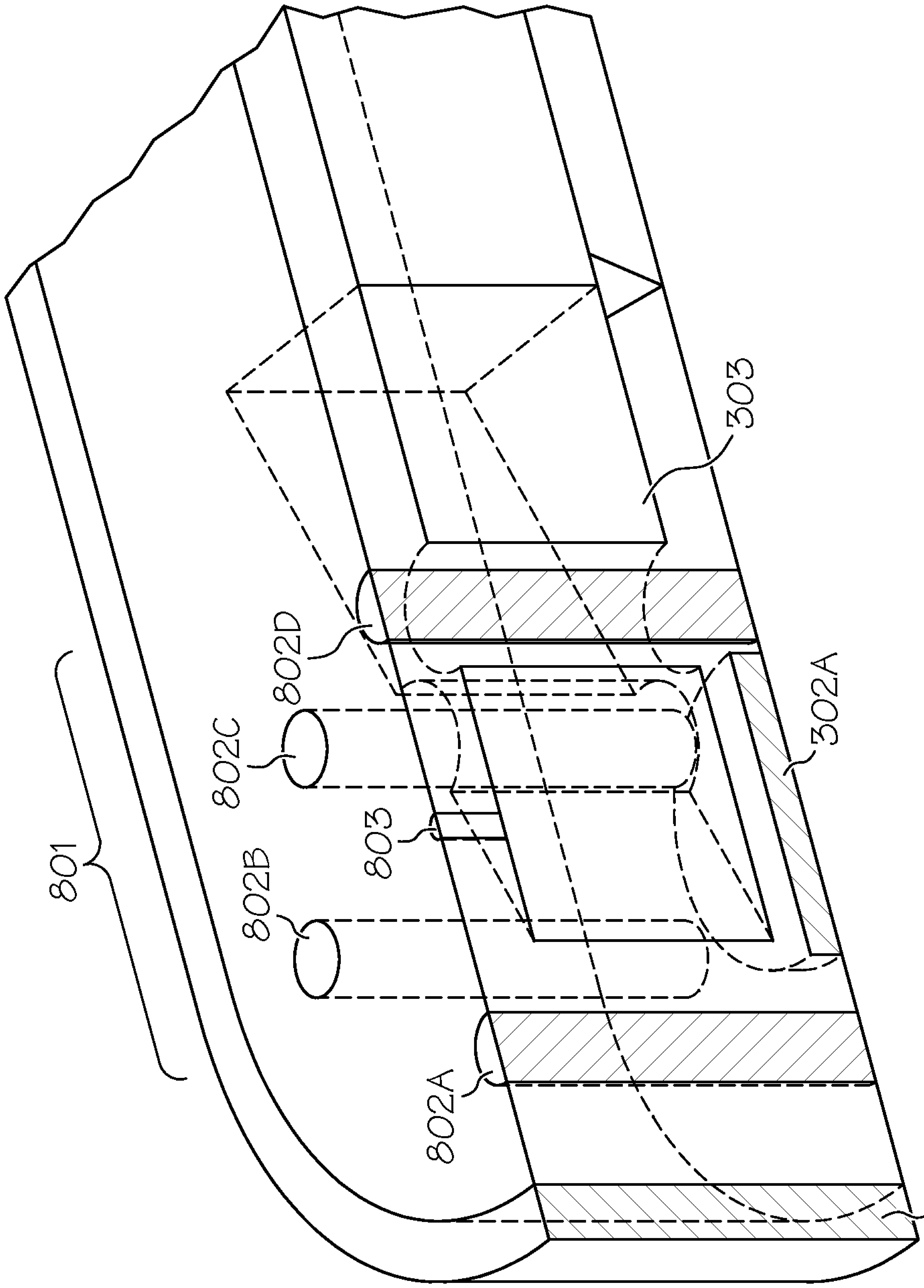

FIG. 8

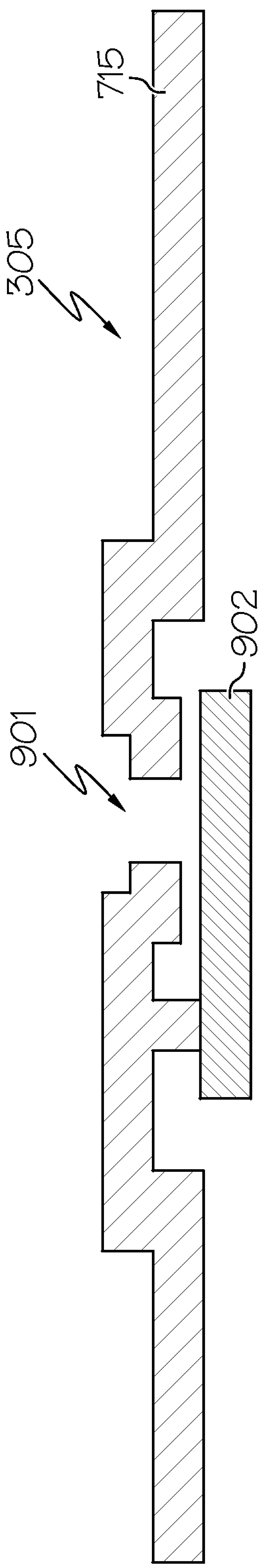

FIG. 9A

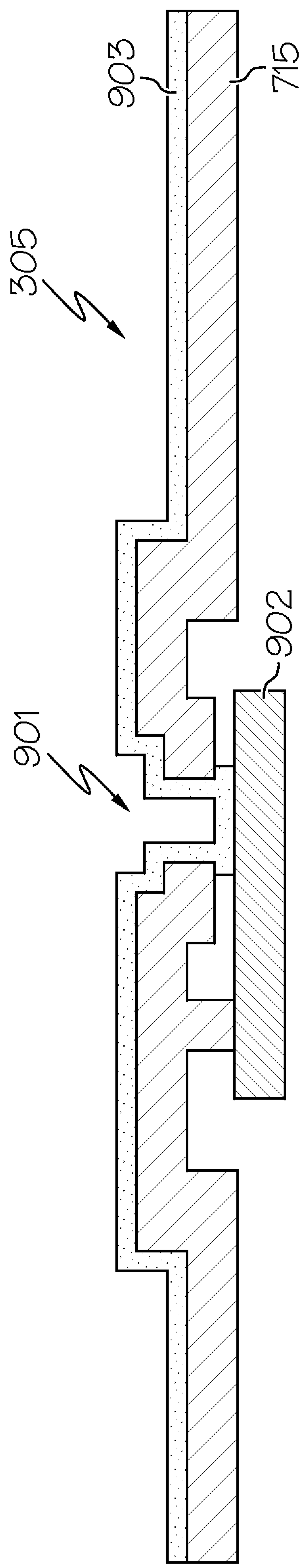

FIG. 9B

DIFFERENTIAL MICROPHONE WITH SEALED BACKSIDE CAVITIES AND DIAPHRAGMS COUPLED TO A ROCKING STRUCTURE THEREBY PROVIDING RESISTANCE TO DEFLECTION UNDER ATMOSPHERIC PRESSURE AND PROVIDING A DIRECTIONAL RESPONSE TO SOUND PRESSURE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to the following commonly owned U.S. patent application:

Provisional Application Ser. No. 61/473,217, "Differential Microphone with Sealed Backside Cavities and Diaphragms Coupled to a Rocking Structure Thereby Providing Resistance to Deflection Under Atmospheric Pressure and Providing a Directional Response to Sound Pressure," filed Apr. 8, 2011, and claims the benefit of its earlier filing date under 35 U.S.C. §119(e).

GOVERNMENT INTERESTS

This invention was made with government support under DC009721 awarded by the National Institutes of Health. The U.S. Government has certain rights in the invention.

TECHNICAL FIELD

The present invention relates generally to miniature microphones, and more particularly to a micromachined differential microphone with sealed backside cavities where the diaphragms are coupled to a rocking structure thereby providing resistance to deflection under external atmospheric pressure and providing a directional response to small dynamic sound pressure.

BACKGROUND

Miniature microphones, which may be used in various applications (e.g., cellular phones, laptop computers, portable consumer electronics, hearing aids), typically include a membrane and a rigid back electrode in close proximity to form a capacitor with a gap. Incoming sound induces vibrations in the compliant membrane and these vibrations change the capacitance of the structure which can be sensed with electronics. Typically, the structure of the microphone contains a large backside cavity and a small pressure release hole. The pressure release hole allows the large atmospheric pressure to reach the backside of the membrane. While the membrane compliance is designed to resolve dynamic pressure vibrations with magnitudes of 1 μPa to 1 Pa, atmospheric pressure is approximately 100 kPa (about a factor of 10^5 times larger). Without a pressure release, it is challenging to design compliant membranes that do not collapse under atmospheric pressure.

Recently, microelectromechanical systems (MEMS) processing has been utilized to fabricate miniature microphones. However, most miniature microphones using MEMS processing use a deep reactive ion etch step through the entire silicon substrate, thereby preventing CMOS compatibility. If, however, miniature microphones could use MEMS processing without the use of the deep reactive ion etch step, then miniature microphones could be manufactured with CMOS compatible processes which have a significant cost advantage over other processes.

Furthermore, there is a desire to create a vacuum sealed microphone. By removing air from the gap, a microphone with much lower self-noise (which results in higher fidelity) can be fabricated with a potentially better frequency response. However, a very stiff diaphragm would be required to prevent the structure from collapsing under external atmospheric pressure, and such a structure would have poor sensitivity to small sound pressure due to its stiffness. Such structures have been manufactured using MEMS processing to realize ultrasound sensors but not functional microphones.

BRIEF SUMMARY

In one embodiment of the present invention, a microphone comprises a first and a second diaphragm, where the first and second diaphragms form a top layer of a first and a second backside sealed cavity. The microphone further comprises a rocking structure coupled to the first and second diaphragms, where the rocking structure rotates on a pivot and where the rocking structure is placed external to the first and second backside sealed cavities.

In another embodiment of the present invention, a microphone comprises a diaphragm, where the diaphragm forms a top layer of a backside sealed cavity. The microphone further comprises a rocking structure coupled to the diaphragm, where the rocking structure rotates on a pivot and where the rocking structure is placed internal in the backside sealed cavity.

In another embodiment of the present invention, a method for fabricating a microphone comprises depositing and patterning a first structural layer to form a first and a second electrode on a substrate. The method further comprises depositing and patterning a first sacrificial layer onto the patterned first structural layer. Additionally, the method comprises performing a dimpled cut in the first sacrificial layer used to create a pivot, where the dimpled cut etches the first sacrificial layer in a manner that leaves a portion of the first sacrificial layer on the substrate. The method further comprises depositing and patterning a second structural layer on the patterned first sacrificial layer to form a first and a second diaphragm, the pivot and a bottom layer of a rocking structure. In addition, the method comprises depositing and patterning additional structural layers to form other layers of the rocking structure.

In another embodiment of the present invention, a method for fabricating a microphone comprises depositing and patterning a first structural layer to form a first and a second electrode on a substrate and a bottom layer of post structures. The method further comprises depositing and patterning a first sacrificial layer onto the patterned first structural layer. Additionally, the method comprises performing a dimpled cut in the first sacrificial layer used to create a pivot, where the dimpled cut etches the first sacrificial layer in a manner that leaves a portion of the first sacrificial layer on the substrate. Furthermore, the method comprises depositing and patterning a second structural layer on the patterned first sacrificial layer to form the pivot and a bottom layer of a rocking structure. In addition, the method comprises depositing and patterning additional structural layers to form other layers of the rocking structure.

The foregoing has outlined rather generally the features and technical advantages of one or more embodiments of the present invention in order that the detailed description of the present invention that follows may be better understood. Additional features and advantages of the present invention will be described hereinafter which may form the subject of the claims of the present invention.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

A better understanding of the present invention can be obtained when the following detailed description is considered in conjunction with the following drawings, in which:

FIG. **1** illustrates a directional microphone configured in accordance with an embodiment of the present invention;

FIG. **2** illustrates an embodiment of the present invention of a top view of the rocking structure of the directional microphone of FIG. **1**;

FIG. **3** illustrates an alternative embodiment of the present invention of a directional microphone;

FIGS. **4**A-**4**B are a flowchart of a method for fabricating the directional microphone of FIG. **1** in accordance with an embodiment of the present invention;

FIGS. **5**A-**5**J depict cross-sectional views of the directional microphone of FIG. **1** during the fabrication steps described in FIGS. **4**A-**4**B in accordance with an embodiment of the present invention;

FIGS. **6**A-**6**B are a flowchart of a method for fabricating the directional microphone of FIG. **3** in accordance with an embodiment of the present invention;

FIGS. **7**A-**7**J depict cross-sectional views of the directional microphone of FIG. **3** during the fabrication steps described in FIGS. **6**A-**6**B in accordance with an embodiment of the present invention;

FIG. **8** illustrates post arranged in a circular manner to support a diaphragm region of the directional microphone of FIG. **3** in accordance with an embodiment of the present invention; and

FIGS. **9**A-**9**B illustrate the process of vacuum sealing the microphone of FIG. **3** in accordance with an embodiment of the present invention.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth to provide a thorough understanding of the present invention. However, it will be apparent to those skilled in the art that the present invention may be practiced without such specific details.

As stated in the Background section, recently, microelectromechanical systems (MEMS) processing has been used to fabricate miniature microphones. However, most miniature microphones using MEMS processing use the deep reactive ion through-wafer etch step thereby preventing CMOS compatibility. If, however, miniature microphones could use MEMS processing without the use of the through-wafer deep reactive ion etch step, then miniature microphones could be manufactured with CMOS compatible processes which have a significant cost advantage over other processes. Furthermore, there is a desire to create a vacuum sealed microphone. By removing air from the gap, a microphone with much lower self-noise (which results in higher fidelity) can be fabricated with a potentially better frequency response. However, a very stiff diaphragm would be required to prevent the structure from collapsing under external atmospheric pressure, and such a structure would have poor sensitivity to small sound pressure due to its stiffness.

The principles of the present invention provide embodiments of a differential microphone (also referred to as a pressure gradient microphone) with sealed backside cavities that can be made with MEMS surface micromachining processes without the use of a through-wafer deep reactive ion etch as discussed further below in connection with FIGS. **1**-**3**, **4**A-**4**B, **5**A-**5**J, **6**A-**6**B, **7**A-**7**J, **8** and **9**A-**9**B. FIG. **1** illustrates one embodiment of a directional microphone with two sealed backside cavities where the motion of two vacuum sealed diaphragms are coupled to an external freely rotating rocking structure. FIG. **2** illustrates a top view of the rocking structure of the directional microphone of FIG. **1**. FIG. **3** illustrates an alternative embodiment of a directional microphone where the rocking structure is contained within a single large vacuum sealed cavity and coupled to two compliant diaphragms along the top of the cavity. FIGS. **4**A-**4**B are a flowchart of a method for fabricating the directional microphone of FIG. **1**. FIGS. **5**A-**5**J depict cross-sectional views of the directional microphone of FIG. **1** during the fabrication steps described in FIGS. **4**A-**4**B. FIGS. **6**A-**6**B are a flowchart of a method for fabricating the directional microphone of FIG. **3**. FIGS. **7**A-**7**J depict cross-sectional views of the directional microphone of FIG. **3** during the fabrication steps described in FIGS. **6**A-**6**B. FIG. **8** illustrates posts arranged in a circular manner to support a diaphragm region of the directional microphone of FIG. **3**; and FIGS. **9**A-**9**B illustrate the process of vacuum sealing the microphone of FIG. **3**.

Referring now to the Figures in detail, FIG. **1** illustrates an embodiment of the present invention of a directional microphone **100** with sealed backside cavities **101**A, **101**B, each containing an electrode **102**A, **102**B, respectively. Backside cavities **101**A-**101**B may collectively or individually be referred to as backside cavities **101** or backside cavity **101**, respectively. Electrodes **102**A-**102**B may collectively or individually be referred to as electrodes **102** or electrode **102**, respectively. In one embodiment, a diaphragm **103**A, **103**B forms a portion of the topside of backside cavities **101**A, **101**B, respectively. Diaphragms **103**A, **103**B may collectively or individually be referred to as diaphragms **103** or diaphragm **103**, respectively.

Microphone **100** may further include a rocking structure or beam **104** coupled to diaphragms **103**. Rocking structure **104** is configured to "rock" or rotate on a pivot **105** as discussed further below. The structure of microphone **100** may reside on a substrate **106**.

In one embodiment, backside cavities **101** are sealed with any gas, including air, and can be sealed under any pressure. In one embodiment, backside cavities **101** are sealed under vacuum so that no gas occupies the cavity.

In one embodiment, a plurality of capacitors are formed between diaphragms **103** and electrodes **102**. In one embodiment, a portion of the capacitors are used for sensing and a portion of the capacitors are used for electrostatic actuation.

In one embodiment, rocking structure **104** provides resistance to deflection under external atmospheric pressure and will provide a directional response to small dynamic sound pressure as discussed below. When sound waves, which are small air pressure oscillations, arrive at microphone **100** in the y direction, as labeled in FIG. **1**, the pressure oscillations impinge on both the right and left diaphragms **103** at the same time. Force is balanced on both sides of rocking structure **104** and there is no induced rocking motion. However, when sound waves arrive from the x direction, as labeled in FIG. **1**, a pressure imbalance exists between the left and right diaphragms **103** due to the finite time it takes for sound to travel across microphone **100**. This pressure imbalance applies a net moment to rocking structure **104** which in turn forces rocking structure **104** and diaphragms **103** into motion. As a result, rocking structure **104** has an inherently directional response to sound. Such a feature is useful as it can enable applications where one can point a microphone in a direction of interest to attain maximum sensitivity while simultaneously filtering out ambient sounds coming from the side that would otherwise affect speech intelligibility and signal-to-noise ratio (SNR).

Furthermore, diaphragms **103** are capable of resisting collapse under atmospheric pressure owing to the stiffness provided by rocking structure **104**. In one embodiment, rocking structure **104** can be made completely insensitive to sound by including perforations into the structure of rocking structure **104** as shown in FIG. **2**. Said perforations also aid in reducing damping of the structure as described below.

FIG. **2** illustrates the top view **200** of rocking structure **104** of directional microphone **100** in accordance with an embodiment of the present invention. Referring to FIG. **2**, in conjunction with FIG. **1**, since rocking structure **104** of directional microphone **100** is external to backside cavities **101**, a small amount of air damping may occur underneath rocking structure **104**. As a result, rocking structure **104** may include perforations **201** as shown in the top view **200** of rocking structure **104**. As a result, air underneath rocking structure **104** can be displaced through these perforations **201** as rocking structure **104** rotates.

Additionally, rocking structure **104** may include a design that is triangular in shape, as shown in top view **200** of rocking structure **104**, where rocking structure **104** is wider along pivot **105** and narrower along its edges in order to minimize the moment of inertia about its rotating axis.

Returning to FIG. **1**, in one embodiment, microphone **100** may be designed to provide additional resistance to deflection under external atmospheric pressure by placing an electrostatic charge of one type (e.g., positive charge) on diaphragms **103** and placing an electrostatic charge of the same type on electrodes **102** thereby forming an electrostatic repulsion between diaphragms **103** and electrodes **102**.

In another embodiment, microphone **100** may be designed to provide additional resistance to deflection under external atmospheric pressure by having diaphragms **103** be made out of a magnetic material (e.g., iron, nickel) which are then magnetized thereby generating a magnetic field. When current is run through diaphragms **103**, the magnetic field exerts an additional upward force on diaphragm **103** to assist in preventing collapse under atmospheric pressure.

As discussed above, when sound waves arrive from the x direction, as labeled in FIG. **1**, a pressure imbalance exists between the left and right diaphragms **103**A and **103**B due to the finite time it takes for sound to travel across microphone **100**. This pressure imbalance applies a net moment to rocking structure **104** which in turn forces rocking structure **104** and diaphragms **103** into motion. The motion of rocking structure **104** and/or diaphragms **103** can be sensed using any number of transduction principles common to MEMS and acoustic sensors, such as piezoelectric, optical, piezoresistive and capacitive. For example, diaphragms **103** may be made electrically conductive so that parallel plate capacitors are formed by the diaphragms **103** and electrodes **102**.

An alternative directional microphone where the rocking structure is sealed along with the electrodes in a backside cavity is discussed below in connection with FIG. **3**.

FIG. **3** illustrates an alternative embodiment of the present invention of a directional microphone **300** with a sealed backside cavity **301** containing electrodes **302**A, **302**B and a rocking structure **303** configured to "rock" or rotate on a pivot **304**. Electrodes **302**A-**302**B may collectively or individually be referred to as electrodes **302** or electrode **302**, respectively. Rocking structure **303** is connected to diaphragms **305**A, **305**B as shown in FIG. **3**. Diaphragms **305**A, **305**B may collectively or individually be referred to as diaphragms **305** or diaphragm **305**, respectively. The structure of microphone **300** may reside on a substrate **306**.

In one embodiment, backside cavity **301** is sealed with any gas, including air, and can be sealed under any pressure. In one embodiment, backside cavity **301** is sealed under vacuum so that no gas occupies the cavity.

In one embodiment, a plurality of capacitors are formed between rocking structure **303** and electrodes **302**. In one embodiment, a portion of the capacitors are used for sensing and a portion of the capacitors are used for electrostatic actuation.

As with the case of directional microphone **100** of FIG. **1**, rocking structure **303** of directional microphone **300** provides resistance to deflection under external atmospheric pressure and will provide a directional response to small dynamic sound pressure as discussed below. When sound waves arrive at microphone **300** in the y direction, as labeled in FIG. **3**, the pressure oscillations impinge on both the right and left diaphragms **305** at the same time. Force is balanced on both sides of rocking structure **303** and there is no induced rocking motion. However, when sound waves arrive from the x direction, as labeled in FIG. **3**, a pressure imbalance exists. This pressure imbalance applied to diaphragms **305** in turn applies a net moment to rocking structure **303** which in turn forces rocking structure **303** and diaphragms **305** into motion. As a result, rocking structure **303** and diaphragms **305** have an inherently directional response to sound.

As with the case with microphone **100**, rocking structure **303** can be designed very stiff to resist deflection under atmospheric pressure acting on each diaphragm **305**. Atmospheric pressure is omnidirectional and therefore the atmospheric pressure is balanced on both diaphragms **305**.

Furthermore, by placing rocking structure **303** inside a cavity **301**, which may be vacuum sealed, the effects of air damping on the motion of rocking structure **303** are eliminated.

In addition, in one embodiment, rocking structure **303** may include a design that is triangular in shape that is similar to the shape shown in the top view **200** of rocking structure **104** (FIG. **2**) in order to minimize the moment of inertia about its rotating axis. Perforations **201** may also be advantageous to further reduce moment of inertia.

Returning to FIG. **3**, the operation of microphone **300** is similar in operation to microphone **100** (FIG. **1**). For example, the motion of rocking structure **303** and/or diaphragms **305** can be sensed using any number of transduction principles common to MEMS and acoustic sensors, such as piezoelectric, optical, piezoresistive and capacitive. For example, the motion of rocking structure **303** can change a capacitance which can be sensed with electronics. For instance, rocking structure **303** may be made electrically conductive so that parallel plate capacitors are formed by the rocking structure **303** and electrodes **302**.

As discussed above, microphones **100** and **300** include two diaphragms **103**, **305** with sealed backside cavities **101**, **301**. In each microphone **100**, **300**, diaphragms **103**, **305** are coupled to a rocking structure **104**, **303** which will provide resistance to deflection under external atmospheric pressure and will provide a directional response to small dynamic sound pressure. Additionally, each microphone **100**, **300** can be manufactured using MEMS surface-micromachining processes without the use of the through-wafer deep reactive ion etch to create a backside cavity. In one embodiment, microphones **100**, **300** can be fabricated using a standard process with alternating sacrificial oxide and polysilicon layers, such as Sandia's SUMMiT™ V 5-level surface micromachining processes or MEMSCAP's poly-MUMPs process, as discussed below in connection with FIGS. **4**A-**4**B, **5**A-**5**J, **6***a*-**6**B, **7**A-**7**J, **8** and **9**A-**9**B. While the following discusses using such a sequence to fabricate microphones **100**, **300**, the principles of the present invention are not limited to such processes but can include other processes to fabricate microphones **100**, **300**. Furthermore, the principles of the present invention are not limited to enacting all the steps of a 5-level surface micromachining process. For example, some of the steps described below may be combined or eliminated, such as by depositing a fewer number of polysilicon and/or sacrificial oxide layers to fabricate the microphones **100**, **300**.

Referring to FIGS. **4**A-**4**B, FIGS. **4**A-**4**B are a flowchart of a method **400** for fabricating directional microphone **100** of FIG. **1**. FIGS. **4**A-**4**B will be discussed in conjunction with FIGS. **5**A-**5**J, which depict cross-sectional views of microphone **100** during the fabrication steps described in FIGS. **4**A-**4**B in accordance with an embodiment of the present invention.

Referring to FIG. **4**A, in conjunction with FIGS. **1** and **5**A-**5**J, in step **401**, a first layer of polysilicon is deposited on substrate **106**. Substrate **106** may be a blank silicon wafer or may be a silicon wafer with electrically insulating layers across its surface, such as silicon dioxide or silicon nitride. In one embodiment, a thickness of approximately 0.3 μm of polysilicon is deposited in step **401**. In step **402**, the first layer of polysilicon is patterned to form electrodes **102**A, **102**B as illustrated in FIG. **5**A.

In step **403**, a first sacrificial oxide layer is deposited onto the patterned first layer of polysilicon (structure of FIG. **5**A). In one embodiment, a thickness of approximately 2 μm of sacrificial oxide is deposited in step **403**. In step **404**, the first sacrificial oxide layer **501** is patterned to define the height of the sealed cavities **101** as illustrated in FIG. **5**B. In one embodiment, the patterning of first sacrificial oxide layer **501** may include making a dimpled cut **511** to create pivot **105** as shown in FIG. **5**B. A "dimpled cut" **511**, as used herein, refers to etching the sacrificial oxide layer **501** so that a portion of sacrificial oxide layer **501** remains above substrate **106**.

In step **405**, a second layer of polysilicon is deposited onto the structure of FIG. **5**B. In one embodiment, a thickness of approximately 1 μm of polysilicon is deposited in step **405**. In step **406**, the second layer of polysilicon is patterned to form diaphragms **103**, pivot **105** and a portion **502** of the lower section of rocking structure **104** as illustrated in FIG. **5**C.

In step **407**, a second sacrificial oxide layer is deposited onto the structure of FIG. **5**C. In one embodiment, a thickness of approximately 0.3 μm of sacrificial oxide is deposited in step **407**. In step **408**, the second sacrificial oxide layer **503** is patterned as illustrated in FIG. **5**D.

In step **409**, a third layer of polysilicon is deposited onto the structure of FIG. **5**D. In one embodiment, a thickness of approximately 1.5 μm of polysilicon is deposited in step **409**. In step **410**, the third layer of polysilicon is patterned to form a portion **504** of the lower section of rocking structure **104** as well as posts **505**A, **505**B on top of diaphragms **103**A, **103**B, respectively, as illustrated in FIG. **5**E. Posts **505**A, **505**B are used to connect the diaphragms **103**A, **103**B to rocking structure **104** as shown further below.

Referring to FIG. **4**B, in conjunction with FIGS. **1** and **5**A-**5**J, in step **411**, a third sacrificial oxide layer is deposited onto the structure of FIG. **5**E. In one embodiment, a thickness of approximately 2 μm of sacrificial oxide is deposited in step **411**. In step **412**, the third sacrificial oxide layer **506** is patterned as illustrated in FIG. **5**F.

In step **413**, a fourth layer of polysilicon is deposited onto the structure of FIG. **5**F. In one embodiment, a thickness of approximately 2.25 μm of polysilicon is deposited in step **413**. In step **414**, the fourth layer of polysilicon is patterned to form a portion **507** of the upper section of rocking structure **104** as well as form touchdowns **508**A, **508**B to diaphragms **103**A, **103**B as illustrated in FIG. **5**G.

In step **415**, a fourth sacrificial oxide layer is deposited onto the structure of FIG. **5**G. In one embodiment, a thickness of approximately 2.0 μm of sacrificial oxide is deposited in step **415**. In step **416**, the fourth sacrificial oxide layer **509** is patterned as illustrated in FIG. **5**H.

In step **417**, a fifth layer of polysilicon is deposited onto the structure of FIG. **5**H. In one embodiment, a thickness of approximately 2.25 μm of polysilicon is deposited in step **417**. In step **418**, the fourth layer of polysilicon is patterned to increase the thickness **510** of the upper section of rocking structure **104** as illustrated in FIG. **5**I.

In step **419**, a release etch is performed to remove the sacrificial oxide as illustrated in FIG. **5**J. In step **420**, cavities **101** may be vacuum sealed via deposition of a thin material layer (e.g., a metal) which fills small etch holes in diaphragms **103**. This sealing step will be described in greater detail below. Pivot **105** will touch down when microphone **100** deflects under atmospheric pressure when sealed.

In some implementations, method **400** may include other and/or additional steps that, for clarity, are not depicted. Further, in some implementations, method **400** may be executed in a different order presented and that the order presented in the discussion of FIGS. **4**A-**4**B is illustrative. Additionally, in some implementations, certain steps in method **400** may be executed in a substantially simultaneous manner or may be omitted.

An embodiment of a method for fabricating directional microphone **300** of FIG. **3** will now be discussed below in connection with FIGS. **6**A-**6**B, **7**A-**7**J, **8** and **9**A-**9**B.

FIGS. **6**A-**6**B are a flowchart of a method **600** for fabricating directional microphone **300** of FIG. **3**. FIGS. **6**A-**6**B will be discussed in conjunction with FIGS. **7**A-**7**J, which depict cross-sectional views of microphone **300** during the fabrication steps described in FIGS. **6**A-**6**B in accordance with an embodiment of the present invention.

Referring to FIG. **6**A, in conjunction with FIGS. **3** and **7**A-**7**J, in step **601**, a first layer of polysilicon is deposited on substrate **306**. In one embodiment, a thickness of approximately 0.3 μm of polysilicon is deposited in step **601**. In step **602**, the first layer of polysilicon is patterned to form electrodes **302**A, **302**B and the bottom layer **701**A, **701**B of the post structures as illustrated in FIG. **7**A.

In step **603**, a first sacrificial oxide layer is deposited onto the patterned first layer of polysilicon (structure of FIG. **7**A). In one embodiment, a thickness of approximately 2 μm of sacrificial oxide is deposited in step **603**. In step **604**, the first sacrificial oxide layer **702** is patterned as illustrated in FIG. **7**B. In one embodiment, the patterning of first sacrificial oxide layer **702** may include making a dimpled cut **703** to create pivot **304** as shown in FIG. **7**B. A "dimpled cut" **703**, as used herein, refers to etching the sacrificial oxide layer **702** so that a portion of sacrificial oxide layer **702** remains above substrate **306**.

In step **605**, a second layer of polysilicon is deposited onto the structure of FIG. **7**B. In one embodiment, a thickness of approximately 1 μm of polysilicon is deposited in step **605**. In step **606**, the second layer of polysilicon is patterned to form pivot **304**, a portion **704** of the lower section of rocking structure **303** as well as to add thickness **705**A, **705**B to the post structures as illustrated in FIG. **7**C.

In step **607**, a second sacrificial oxide layer is deposited onto the structure of FIG. **7**C. In one embodiment, a thickness of approximately 0.3 μm of sacrificial oxide is deposited in step **607**. In step **608**, the second sacrificial oxide layer **706** is patterned as illustrated in FIG. **7**D.

In step **609**, a third layer of polysilicon is deposited onto the structure of FIG. **7**D. In one embodiment, a thickness of approximately 1.5 μm of polysilicon is deposited in step **609**. In step **610**, the third layer of polysilicon is patterned to form a portion **707** of the lower section of rocking structure **303** as well as to add thickness **708**A, **708**B to the post structures as illustrated in FIG. **7**E.

Referring to FIG. **6**B, in conjunction with FIGS. **3** and **7**A-**7**J, in step **611**, a third sacrificial oxide layer is deposited onto the structure of FIG. **7**E. In one embodiment, a thickness of approximately 2 μm of sacrificial oxide is deposited in step **611**. In step **612**, the third sacrificial oxide layer **709** is patterned to form posts **710**A, **710**B on post structures **701**, **705**, **708** as illustrated in FIG. **7**F.

In step **613**, a fourth layer of polysilicon is deposited onto the structure of FIG. **7**F. In one embodiment, a thickness of approximately 2.25 μm of polysilicon is deposited in step **613**. In step **614**, the fourth layer of polysilicon is patterned to form a portion **711** of the upper section of rocking structure **303** as well as to add thickness **712**A, **712**B to the post structures as illustrated in FIG. **7**G.

In step **615**, a fourth sacrificial oxide layer is deposited onto the structure of FIG. **7**G. In one embodiment, a thickness of approximately 2.0 μm of sacrificial oxide is deposited in step **615**. In step **616**, the fourth sacrificial oxide layer **713** is patterned to form a portion **714** of the upper section of rocking structure **303** as well as form to posts **715**A, **715**B on post structures **701**, **705**, **708**, **710**, **712** as illustrated in FIG. **7**H.

In step **617**, a fifth layer of polysilicon is deposited onto the structure of FIG. **7**H. In one embodiment, a thickness of approximately 2.25 μm of polysilicon is deposited in step **617**. In step **618**, the fifth layer of polysilicon **716** is patterned to increase the thickness of the upper section of rocking structure **303** and the post structures as illustrated in FIG. **7**I.

In step **619**, a release etch is performed to remove the sacrificial oxide as illustrated in FIG. **7**J. In step **620**, cavity **301** is vacuum sealed as discussed further below.

In some implementations, method **600** may include other and/or additional steps that, for clarity, are not depicted. Further, in some implementations, method **600** may be executed in a different order presented and that the order presented in the discussion of FIGS. **6**A-**6**B is illustrative. Additionally, in some implementations, certain steps in method **600** may be executed in a substantially simultaneous manner or may be omitted.

An additional view of the top surface of microphone **300** is provided below in connection with FIG. **8**. FIG. **8** illustrates a portion of the top surface of microphone **300** that includes a circular pattern of posts that extends from the top surface of microphone **300** to the substrate in accordance with an embodiment of the present invention.

Referring to FIG. **8**, in conjunction with FIGS. **3**, **6**A-**6**B and **7**A-**7**J, a diaphragm region **801** is formed by the free membrane between various posts **802**A-D arranged in a circular or any other manner. Posts **802**A-D may collectively or individually be referred to as posts **802** or post **802**, respectively. While FIG. **8** illustrates four posts **802** arranged in a circular manner, any number of posts **802** may be arranged in a circular manner. In one embodiment, posts **802** extend from the top surface of microphone **300** to the substrate level **306**. Additionally, a post **803** connects the center of diaphragm **305** to rocking structure **303**. Furthermore, a rigid side-wall **804** may surround microphone **300** as illustrated in FIG. **8**.

FIGS. **9**A and **9**B illustrate the process of vacuum sealing microphone **300** in accordance with an embodiment of the present invention. Referring to FIG. **9**A, in conjunction with FIGS. **3**, **6**A-**6**B and **7**A-**7**J, an etch release hole **901** exists at a portion of the top surface layer **716** of microphone **300**. Etch release hole **901** is used so that the sacrificial oxide can be removed in step **619**. A portion of an underlying polysilicon layer (e.g., polysilicon layer **711**) is structured as a lip **902** that is used to collect a sealant (e.g., a metal applied during a sputtering or evaporation process step) when it is applied to the top surface layer **716** of microphone **300**, thereby forming a sealing layer **903** as illustrated in FIG. **9**B. This same technique is applicable to microphone **100** (FIG. **1**), in which case the etch hole should reside on diaphragm **103** (FIG. **1**).

The descriptions of the various embodiments of the present invention have been presented for purposes of illustration, but are not intended to be exhaustive or limited to the embodiments disclosed. Many modifications and variations will be apparent to those of ordinary skill in the art without departing from the scope and spirit of the described embodiments. The terminology used herein was chosen to best explain the principles of the embodiments, the practical application or technical improvement over technologies found in the marketplace, or to enable others of ordinary skill in the art to understand the embodiments disclosed herein.

The invention claimed is:

1. A microphone comprising:

a first diaphragm and a second diaphragm, wherein said first and second diaphragms form a top layer of a first backside sealed cavity and a second backside sealed cavity, wherein said first and second backside sealed cavities are sealed under a reduced pressure less than that of an ambient pressure that exists outside of said first and second backside sealed cavities; and

a rocking structure coupled to said first and second diaphragms, wherein said rocking structure rotates on a pivot, wherein said rocking structure is placed external to said first and second backside sealed cavities.

2. The microphone as recited in claim **1**, wherein said first and second backside sealed cavities comprise a first electrode and a second electrode, respectively.

3. The microphone as recited in claim **2**, wherein said first and second diaphragms are electrically conductive, wherein parallel plate capacitors are formed between said first and second diaphragms and said first and second electrodes, respectively.

4. The microphone as recited in claim **2**, wherein an electrostatic charge is placed on said first and second diaphragms and an electrostatic charge of a same type is placed on said first and second electrodes.

5. The microphone as recited in claim **1**, wherein said first and second backside sealed cavities comprise a plurality of electrodes thereby forming a plurality of capacitors between said first and second diaphragms and said plurality of electrodes.

6. The microphone as recited in claim **5**, wherein a portion of said plurality of capacitors are used for sensing, wherein a portion of said plurality of capacitors are used for electrostatic actuation.

7. The microphone as recited in claim **1**, wherein said first and second backside sealed cavities are vacuum sealed.

8. The microphone as recited in claim **1**, wherein said rocking structure turns into motion when pressure arrives from a horizontal direction.

9. The microphone as recited in claim **1**, wherein said first and second diaphragms are repulsed upwards by use of magnetic forces.

10. The microphone as recited in claim **9**, wherein current is run through said first and second diaphragms thereby creating a magnetic field.

11. A microphone comprising:

a diaphragm, wherein said diaphragm forms a top layer of a backside sealed cavity wherein said backside sealed cavity; comprises a first electrode and a second electrode;

a rocking structure coupled to said diaphragm, wherein said rocking structure rotates on a pivot, wherein said rocking structure is placed internal in said backside sealed cavity, and wherein said rocking structure is electrically conductive, wherein parallel plate capacitors are formed between said rocking structure and said first and second electrodes.

12. The microphone as recited in claim **11**, wherein said first and second electrodes are positioned beneath said rocking structure.

13. The microphone as recited in claim **11**, wherein an electrostatic charge is placed on said diaphragm and an electrostatic charge of a same type is placed on said first and second electrodes.

14. The microphone as recited in claim **11**, wherein said backside sealed cavity comprises a plurality of electrodes thereby forming a plurality of capacitors between said rocking structure and said plurality of electrodes.

15. The microphone as recited in claim **14**, wherein a portion of said plurality of capacitors are used for sensing, wherein a portion of said plurality of capacitors are used for electrostatic actuation.

16. The microphone as recited in claim **11**, wherein said backside sealed cavity is vacuum sealed.

17. The microphone as recited in claim **11**, wherein said rocking structure turns into motion when pressure arrives from a horizontal direction.

18. The microphone as recited in claim **11**, wherein said diaphragm is repulsed upwards by use of magnetic forces.

19. The microphone as recited in claim **18**, wherein current is run through said diaphragm thereby creating a magnetic field.

20. The microphone as recited in claim **11**, wherein a plurality of posts extend from a top surface of said microphone to a substrate of said microphone.

21. The microphone as recited in claim **20**, wherein said posts protrude through holes in said rocking structure.

* * * * *